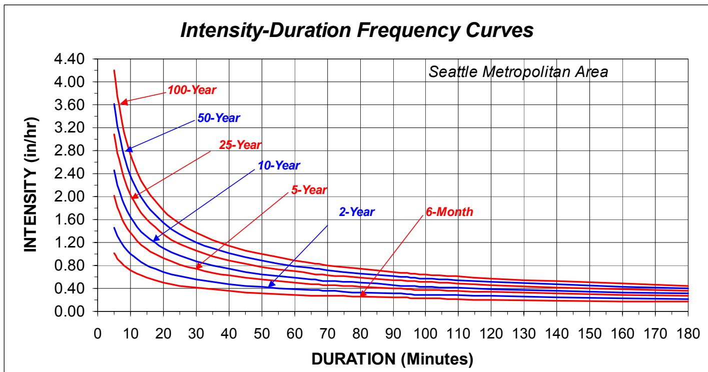
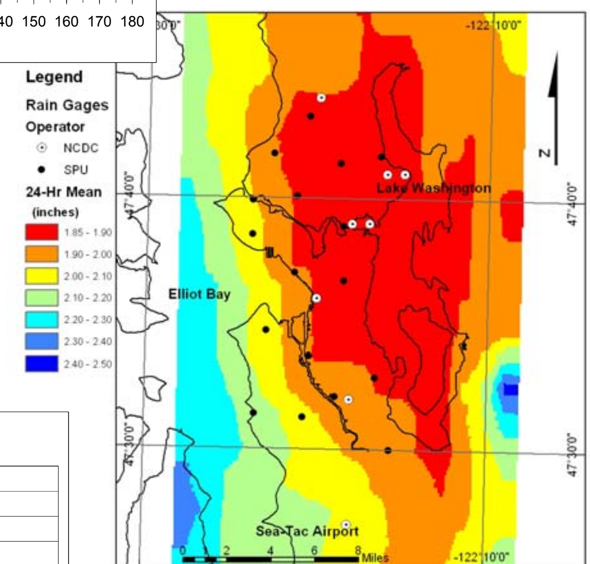
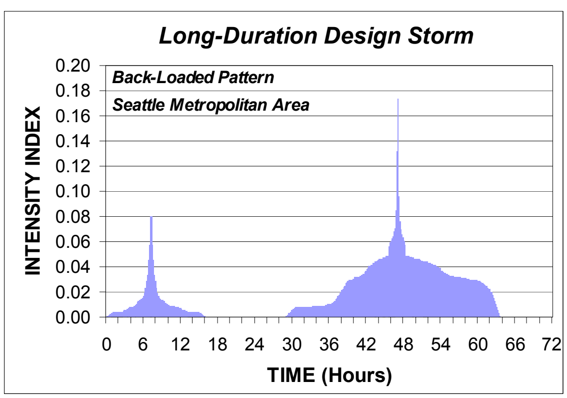
ANALYSES OF PRECIPITATION-FREQUENCY AND STORM CHARACTERISTICS FOR THE CITY OF SEATTLE







Seattle Public Utilities

December 2003

MGS Engineering Consultants, Inc.

ANALYSES OF PRECIPITATION-FREQUENCY AND STORM CHARACTERISTICS FOR THE CITY OF SEATTLE

Prepared for:

Seattle Public Utilities

By:

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ANALYSES OF PRECIPITATION-FREQUENCY AND STORM CHARACTERISTICS FOR THE CITY OF SEATTLE

EXECUTIVE SUMMARY

Analyses of precipitation-frequency and storm characteristics were conducted to develop products for use in design and analysis of stormwater projects in the Seattle Metropolitan Area. Seattle Public Utilities (SPU) has operated a 17 gage precipitation measurement network within the City of Seattle since 1965. Precipitation annual maxima data series were assembled using data from the SPU gaging network and the national NOAA cooperative network for durations of 5-min; 10-min; 15-min; 20-min; 30-min; 45-min; 60-min; 2-hr; 3-hr; 6-hr; 12-hr; 24-hr; 48-hr; 72-hr; and 7-days. These data provided the basis for all precipitation-frequency and storm analyses.

Regional precipitation-frequency analyses were conducted for the 15 durations from 5-minutes through 7-days. The three-parameter Generalized Extreme Value (GEV) distribution was found to be the best choice for describing the precipitation magnitude-frequency characteristics in the Seattle Metropolitan Area. This is the same probability distribution found to be applicable to homogeneous climatic regions in large-scale regional studies conducted for both Washington State and Southern British Columbia. Regional L-moment statistics were used to develop precipitation magnitude-frequency relationships applicable to sites in the Seattle area for each of the 15 durations. This information can be used for computing precipitation magnitude-frequency estimates for any site in the Seattle Metropolitan Area for any of the 15 durations

The Seattle Metropolitan Area was found to be homogeneous with regard to the magnitude-frequency characteristics of short-duration precipitation with durations of 3-hours or less. One set of Intensity-Duration-Frequency (IDF) curves were developed for durations from 5-minutes through 180-minutes that are applicable to the Seattle Metropolitan Area.

The Seattle Metropolitan Area was found to be heterogeneous with regard to the magnitude-frequency characteristics of longer-duration precipitation. Isopluvial maps are needed to describe the spatial variation of precipitation for durations of 6-hours and longer. Gridded datasets of at-site mean values were prepared for the Seattle Metropolitan Area to describe the spatial variability of precipitation for durations of 6-hr, 12-hr, 24-hr, 48-hr, 72-hr and 7-days. These gridded datasets can be used to develop isopluvial maps for any recurrence intervals of interest.

Storm characteristics were measured for noteworthy storms that were recorded by the SPU gaging network. Statistical analyses were conducted for the storm characteristics and dimensionless design storms were developed for short, intermediate, and long-duration storm events. The short, intermediate, and long-duration design storms can be scaled to any site-specific recurrence interval using precipitation magnitudes at the 2-hour, 6-hour and 24-hour durations, respectively.

Analyses were conducted at adjacent precipitation gages to determine the suitability of transposing data for fill-in of missing records. It was found that transposition is generally reasonable for precipitation produced by long-duration storms when the inter-gage distance is several miles or less. Transposition of time-series data is generally inappropriate for precipitation produced by short-duration storms and periods during storms with bursts of high-intensity precipitation unless several nearby gages can corroborate the temporal pattern of precipitation.

ACKNOWLEDGEMENTS
The project plan and topics for this study were developed by Dr. Hirod Gill of the Drainage and Wastewater Program. An advisory group from the Resource Planning Division of Seattle Public Utilities provided assistance and input over the course of this study. The assistance, comments and suggestions from Dr. Gill and the advisory group are greatly appreciated.

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INTRODUCTION

Information about precipitation magnitudes and storm characteristics in the Seattle Metropolitan Area is used for a variety of purposes. Precipitation information is used for conveyance design for sizing culverts and other hydraulic structures. It is used in stormwater rainfall-runoff modeling in the design and analysis of stormwater detention and stormwater treatment facilities. It is used in investigating local flooding problems and for risk management of urban flooding problems. Precipitation information is also used in Seattle's Stormwater Design Manual for regulating construction and development projects for control of stormwater and for water quality treatment of stormwater.

Many of the data sources and design products currently used by SPU for providing precipitation information were developed in the 1960's and 1970's. Since that time, the City of Seattle has operated a network of 17 precipitation gages and collected data on precipitation magnitudes and storm characteristics. There has been a desire by the City to update the original precipitation information with the data from this network of gages. In response, this study was authorized to update the precipitation information for the Seattle Metropolitan Area and to incorporate the latest technologies in providing design products for stormwater management for use by Seattle Public Utilities and by developers of residential and commercial properties.

This report contains descriptions of the analyses of precipitation characteristics and the findings of those analyses for the Seattle Metropolitan Area. It also contains updated precipitation products for use in project design and analysis including:

- Intensity-Duration-Frequency Curves;
- Dimensionless Design Storms for Short, Intermediate and Long-Duration Storms;
- Dimensionless Hyetographs of Noteworthy Historical Storms;
- Precipitation-Frequency Relationships for Durations of 5-min, 10-min, 15-min, 20-min, 30-min, 45-min, 60-min, 2-hr, 3-hr, 6-hr, 12-hr, 24-hr, 48-hr, 72-hr and 7-day durations;
- Gridded datasets of precipitation at-site mean values for use in constructing isopluvial maps for selected recurrence intervals for the 6-hour through 7-day durations.

OVERVIEW

The findings of precipitation-frequency analyses provide the foundation for all of the design and analysis products listed above. Accordingly, the findings of the regional precipitation-frequency analyses will be presented first in this report and will be followed by development of the various design and analysis products. Staff at Seattle Public Utilities (SPU) expressed a high interest in examination of the homogeneity of precipitation within the city limits. Homogeneity of precipitation has been examined in this study as it applies to each design and analysis product that is developed.

PRECIPITATION GAGES USED IN ANALYSES

There are several types of precipitation gages and records that were available for conducting this analysis. This included the 17 gage precipitation network operated by the City of Seattle and gages that are part of the National Oceanic and Atmospheric Administration[13] (NOAA) cooperative network.

City of Seattle Precipitation Gages

The gages operated by the City of Seattle are tipping bucket gages (TB) that measure precipitation with a resolution of 0.01-inch and have event reporting on a 1-minute interval. Operation of the City of Seattle gaging network began in 1965 and data are stored in two electronic formats.

For the period from 1965 through 1977, precipitation maxima for selected durations are stored as storm summary information. A storm was defined as an event with precipitation of 0.25-inch or greater in a 24-hour period, or precipitation of 0.10-inch or greater in a 1-hour period. A storm began with measurable precipitation and ended when a dry period of 3-hours or more occurred. These "storms" were analyzed by the City of Seattle and the maximum precipitation were computed for durations of 5-min, 10-min, 15-min, 20-min, 30-min, 45-min, 60-min, 90-min, 2-hr, 3-hr, 6-hr, 12-hr, 18-hr and 24-hr. A database of the maxima for the 1965-1977 period was created and given the term *Storm Summaries*. The original 1-minute precipitation time-series were reportedly converted to 1-hour time-series but have since been either destroyed or lost. Whatever the case, time-series data for the period from 1965-1977 were not available for this study. As a result, no data from the 1965-1977 period were available for analyses of 48-hr, 72-hr or 7-day precipitation.

For the period from 1978 to present, precipitation time-series are available on a 1-minute time interval for all gages. Time-series data for these gages were aggregated to produce a precipitation time-series for each gage with a fixed 5-minute time interval and provided the basis for this study.

National Oceanic and Atmospheric Administration (NOAA) Precipitation Gages

NOAA non-recording gages[11,13] (daily gage, DY) are standard US Weather Bureau gages that are simple straight-sided cylinders with a diameter of 8-inches that are open to the atmosphere. Precipitation is measured manually once each day at a fixed time and the precipitation for the prior 24-hours is reported to a resolution of 0.01-inch.

NOAA automated gages[12,13] include a variety of weighing bucket and tipping bucket gages. Automated gages were first installed in 1940 and consisted of weighing bucket devices that were given the generic name of hourly gages (HR). Precipitation was mechanically measured, recorded on paper strip charts, and reported on hourly intervals at a resolution of 0.01-inch. These gages were replaced by tipping bucket gages in the early 1970's with the majority of gages having a resolution of 0.10-inch and reporting on hourly intervals. A limited number of NOAA automated gages (FP) report on 15-minute intervals and some have a resolution of 0.01-inch. Data collected at these gages is published through the National Climatic Data Center[11,12] (NCDC). The precipitation gages that were used in these analyses are listed in Tables 1a,b,c and their geographical locations are shown in Figure 1.

ANNUAL MAXIMA DATA SERIES

All precipitation analyses conducted for this study utilized precipitation annual maxima data series. An annual maxima series is assembled by scanning the precipitation record from a given gage and identifying the maximum precipitation amount that has occurred during a given duration during a fixed 12-month period. There are no other constraints in assembling annual maxima series regarding the need to define a storm or checking for intermittent dry periods. This process yields an annual maxima dataset with the number of data equal to the number of years of record. The water-year, October 1st through September 30th, was used to define the annual period. Numerous durations were of interest in this study to provide for development of intensity-duration-frequency relationships, design storms, and for the development of isopluvial maps for selected durations and recurrence intervals. Accordingly, annual maxima data series were assembled for all gages for durations of interest that included: 5-min; 10-min; 15-min; 20-min; 30-min; 45-min; 60-min; 2-hr; 3-hr; 6-hr; 12-hr; 24-hr; 48-hr; 72-hr; and 7-day.

Table 1a – City of Seattle Precipitation Gages Used in Analyses for All Durations

STATION ID	STATION NAME	LATITUDE	LONGITUDE	YEAR START	YEAR END	GAGE TYPE	MEAN ANNUAL PRECIPITATION (in)	
							1978-2002	PRISM[3,12]
45-S001	Haller Lake Shop	47.7211	122.3431	1965	2003	TB	33.4	36.2
45-S002	Mathews Beach Pump Stn	47.6950	122.2731	1969	2003	TB	34.8	36.5
45-S003	UW Hydraulics Lab	47.6481	122.3081	1965	2003	TB	31.4	36.7
45-S004	Maple Leaf Reservoir	47.6900	122.3119	1965	2003	TB	35.5	35.7
45-S005	Fauntleroy Ferry Dock	47.5231	122.3919	1968	2003	TB	30.1	37.5
45-S007	Whitman Middle School	47.6961	122.3769	1965	2003	TB	34.3	36.2
45-S008	Ballard Locks	47.6650	122.3969	1965	2003	TB	33.2	36.7
45-S009	Woodland Park Zoo	47.6681	122.3539	1965	2003	TB	30.8	36.2
45-S010	Rainier Ave Elementary	47.5000	122.2600	1968	2003	TB	35.6	37.1
45-S011	Metro-KC Denny Regulatng	47.6169	122.3550	1970	2003	TB	29.2	36.2
45-S012	Catherine Blaine Jr	47.6419	122.3969	1965	2003	TB	33.0	36.7
45-S014	West Seattle High School	47.5781	122.3819	1965	2003	TB	34.8	36.4
45-S015	Metro-KC Diagonal Pump	47.5619	122.3400	1965	2003	TB	33.7	36.4
45-S016	Metro-KC E Marginal Way	47.5350	122.3139	1970	2003	TB	32.6	36.8
45-S017	West Seattle Engr Shop	47.5211	122.3450	1965	2003	TB	39.7	37.4
45-S018	Hillman Engr Shop	47.5481	122.2750	1965	2003	TB	34.8	36.6
45-S020	TT Minor Elementary	47.6119	122.3069	1975	2003	TB	33.8	36.4

Table 1b – NOAA Automated Gages Used in Analyses for Durations of 1-Hour to 7-Days

STATION ID	STATION NAME	LATITUDE	LONGITUDE	YEAR START	YEAR END	GAGE TYPE	PRISM[3,12] MEAN ANNUAL PRECIPITATION (in)
45-0324	Auburn	47.3167	122.2333	1954	1977	HR	38.5
45-0986	Burlington	48.4667	122.3167	1941	2002	HR	36.5
45-1146	Carnation 4 NW	47.6833	121.9833	1941	2002	HR	49.0
45-1277	Centralia 1W	46.7000	122.9667	1978	2002	FP	46.1
45-2675	Everett	47.9833	122.1833	1941	2002	FP	37.4
45-5149	Mc Chord AFB	47.1500	122.4833	1941	1979	HR	39.8
45-5224	Mc Millin Reservoir	47.1333	122.2667	1941	2002	HR	41.5
45-7458	Seattle Urban Site	47.6500	122.3000	1973	1998	HR	37.4
45-7473	Seattle Tacoma Airport	47.4500	122.3000	1965	2002	HR	37.9
45-7488	Seattle WSO City	47.6000	122.3333	1940	1965	HR	36.8

Table 1c – NOAA Daily Gages Used in Analyses for Durations of 24-Hours to 7-Days

STATION ID	STATION NAME	LATITUDE	LONGITUDE	YEAR START	YEAR END	GAGE TYPE	PRISM[3,12] MEAN ANNUAL PRECIPITATION (in)
45-0176	Anacortes	48.5000	122.6000	1931	2002	DY	27.5
45-0257	Arlington	48.2000	122.1333	1936	2002	DY	47.0
45-4169	Kent	47.4000	122.2333	1912	2002	DY	38.7
45-5525	Monroe	47.8333	121.9833	1929	2002	DY	49.6
45-5678	Mount Vernon 3 WNW	48.4500	122.3667	1956	2002	DY	33.8
45-6803	Puyallup 2W Exp Station	47.2000	122.3333	1914	1995	DY	40.6
45-7459	Seattle Jackson Park	47.7333	122.3333	1941	1986	DY	36.5
45-7468	Seattle Naval Air Station	47.6833	122.2667	1948	1964	DY	37.5
45-7470	Seattle Sand Point WSFO	47.6833	122.2500	1987	2002	DY	37.5
45-7478	Seattle Univ of Wash	47.6500	122.2833	1909	1998	DY	37.2
45-7483	Seattle WB Airport	47.5333	122.3000	1948	1965	DY	36.8
45-7507	Sedro Woolley	48.5000	122.2333	1898	2000	DY	44.2
45-8278	Tacoma 1	47.2333	122.4000	1935	2002	DY	38.5

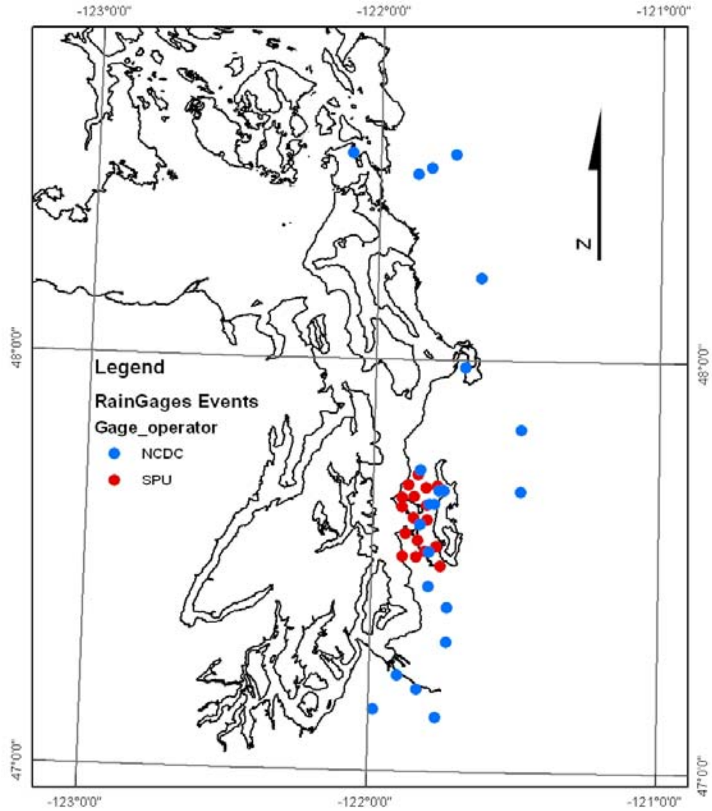


Figure 1 – Geographical Layout of SPU and NOAA Precipitation Gages Used in Analyses

PRECIPITATION MAGNITUDE-FREQUENCY

The findings from regional precipitation-frequency analysis provide the basic information needed for development or implementation of several precipitation-related applications. These applications include: development of intensity-duration-frequency relationships; development of precipitation magnitude-frequency relationships for selected sites; and development of isopluvial maps for selected recurrence intervals and durations.

L-moment statistical analysis techniques (Hosking[5]) with a regional framework were used in this study for computing precipitation magnitude-frequency relationships at the various gage sites. L-moments (Appendix A) are an alternative system for describing the shapes of probability distributions, computing sample statistics, and fitting of distribution parameters to observed data (Hosking and Wallis[6]). They are particularly well-suited to analysis of environmental data that typically exhibit significant skewness. L-Cv and L-Skewness are analogous to the product moment coefficients of variation and skewness, respectively. Regional values of L-Cv and L-Skewness are obtained as weighted values of the at-site values of L-Cv and L-skewness where the at-site values are weighted by record length. Thus, sample statistics with the longest record length are given the greatest credence.

In regional precipitation-frequency analysis, a homogeneous region is one where all sites within the region can be described by a common probability distribution with common distribution parameters after being scaled by the at-site mean. Thus, all sites have a common regional magnitude-frequency curve (termed a regional growth curve, Figure 2) that becomes site-specific after scaling by the at-site mean of the data from the specific site of interest. Thus,

$$P_i\,(F) = \hat{\mu}_i \; p(F) \tag{1}$$

where $P_i\,(F)$ is the at-site inverse Cumulative Distribution Function (CDF), $\hat{\mu}_i$ is the estimate of the population at-site mean (inches), and $p(F)$ is the regional growth curve, regional inverse CDF. This is often called an index-flood approach to regional frequency analyses and was first proposed by Dalrymple[2] and expanded by Wallis[6].

This regional approach equates to a common probability distribution with common coefficients of variation and skewness. This can be visualized graphically as a precipitation-frequency curve with common slope and shape for all sites when the precipitation-frequency curve is expressed in dimensionless form. Figure 2 depicts a regional growth curve (dimensionless precipitation-frequency curve) where precipitation magnitudes are expressed as a ratio to the at-site mean. The relationships between non-exceedance probability, annual exceedance probability, and recurrence interval for use with annual maxima data are:

$$AEP = 1 - F \tag{2a}$$

$$T = \frac{1}{AEP} \tag{2b}$$

where: F is the annual non-exceedance probability; AEP is the annual exceedance probability; and T is recurrence interval in years.

Figure 3 shows the homogeneous regions that were used in developing the precipitation-frequency maps for western Washington as part of a recent large-scale precipitation-frequency study for western Washington (Schaefer[19]). It is seen in Figure 3 that the City of Seattle resides in Climatic Zone 31. This zone is titled *Interior Lowlands East* and all of the precipitation gages selected for use in these analyses were from the Interior Lowlands East climatic zone.

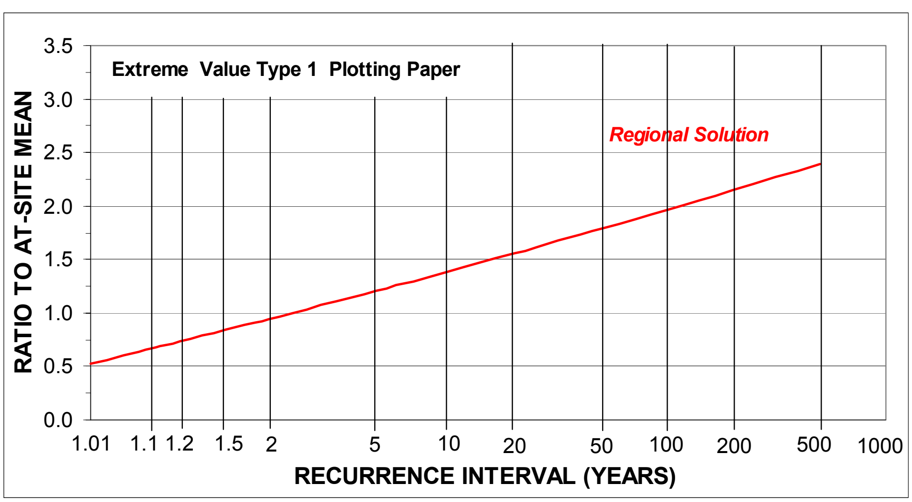


Figure 2 – Dimensionless Precipitation-Magnitude Frequency Curve

Confirmation of Homogeneity for Selected Gages

The candidate homogeneous region for this study was selected as all sites/gages within the Interior Lowlands East Climatic Zone 31 (Figure 3) with a mean annual precipitation between 25-inches and 50-inches. This selection was based on the findings of prior regional studies[16,17,19]. This region includes the 17 gages in the City of Seattle gaging network and the other NOAA gages listed in Tables 1b,c. L-moment sample statistics[5,6] were computed for each of the annual maxima data series for each of the 15 durations at the various gages.

Heterogeneity tests for L-Cv and L-skewness have been developed by (Hosking and Wallis[6]) for assessing the magnitude of heterogeneity of the sample statistics for a proposed region. The test measure H1 examines the variability of sample estimates of L-Cv for the various gages and H2 measures the variability of sample estimates of L-skewness. In those tests, the observed variability in at-site estimates of L-Cv and L-skewness are compared to the variability expected, if in-fact, the data/region were actually homogeneous. Separate heterogeneity tests were conducted for the 17 City of Seattle gages, the collection of gages operating in the 1965-2003 period, and the collection of gages for the full period of record at each gage. The L-moment sample statistics were found to be acceptably homogeneous in 66 of the 68 tests. This confirmed the homogeneity of the proposed candidate region for each of the 15 durations and the use of fixed values of L-Cv and L-skewness for each of the 15 durations.

Regional Values of L-Cv and L-Skewness

After homogeneity criteria H1 and H2 had been satisfied, the regional L-Cv and L-skewness values computed for this study were compared with the findings of large-scale studies (Schaefer[16,17,19]). Appropriate values for L-Cv for the various durations were determined by regression analyses using the results from this study and the findings from prior large scale studies (Figures 4a,b). The use of regression analysis had the benefit of reducing the variance associated with sampling variability and provided a convenient method for smoothing of the L-Cv values in defining the relationship of L-Cv with duration. The adopted L-Cv values are shown in Figure 5 and listed in Table 2.

The behavior of L-Cv values in Figure 5 reflects the influence of two separate storm types. Isolated convective cells and convective cells embedded within synoptic-scale general storms produce the majority of annual maxima at the shorter durations and affect L-Cv values for the upper limb of the relationship. Long-duration general storms and sequences of storms produce the annual maxima at the longer durations and affect L-Cv values for the lower limb of the relationship. A variety of storm types produce a mixed population of annual maxima for durations from roughly 6-hours through 24-hours that results in a transition between the lower and upper limbs of the relationship.

A comparison of observed L-skewness for the period from 1965-2003 and the findings from prior large-scale regional studies is shown in Figure 6a. The general shape of the relationship is seen to be similar to that for L-Cv (Figure 5), except that there is much higher sampling variability associated with L-Skewness. In particular, the regional L-Skewness values for durations of 5-minutes through 30-minutes are based on a small sample of 17 gages, each with about 37-years of record. For this reason, greater emphasis was given to the findings of large-scale regional precipitation analyses (Schaefer[16,17,19]) in determining the L-Skewness values. The adopted values of L-Skewness are shown in Figure 6b and listed in Table 2.

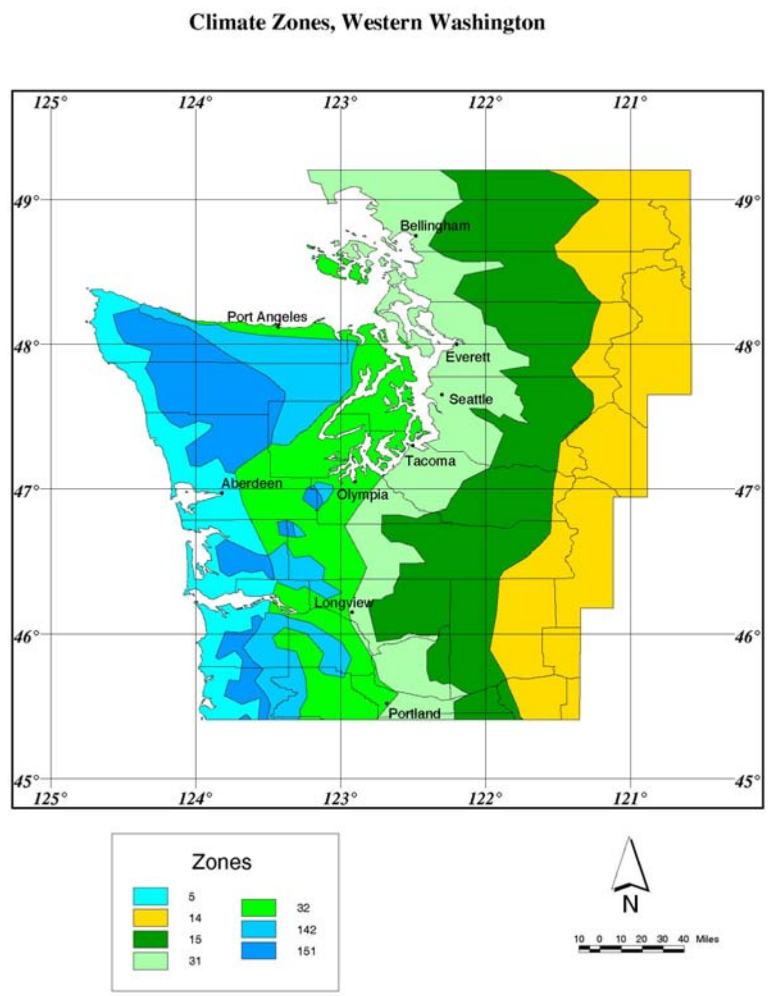


Figure 3 – Map of Western Washington Showing Homogeneous Climatic Regions for Use in Regional Precipitation-Frequency Analysis

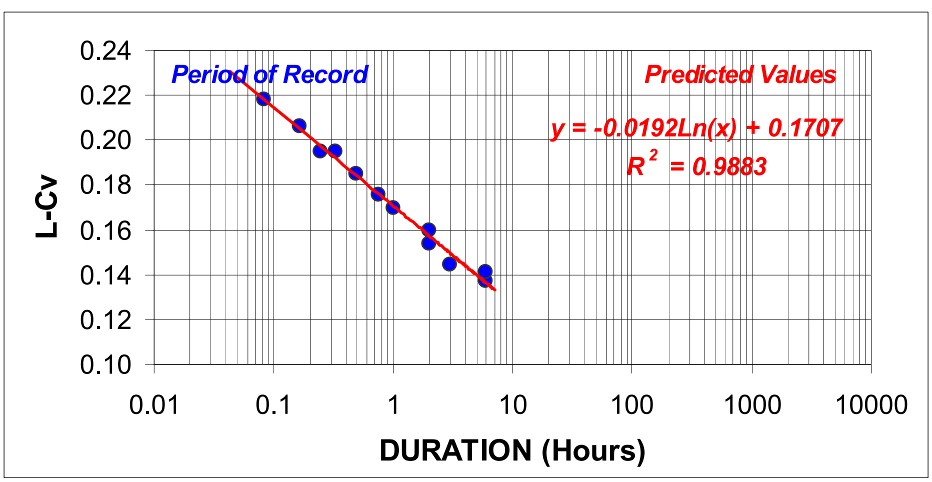


Figure 4a – Regression Solution of L-Cv for Durations of 5-Minutes through 6-Hours

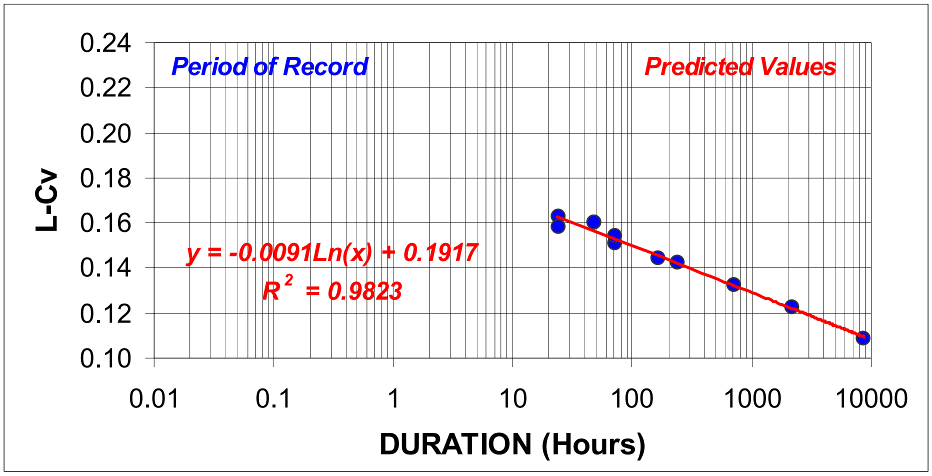


Figure 4b – Regression Solution of L-Cv for Durations of 24-Hours through 7-Days

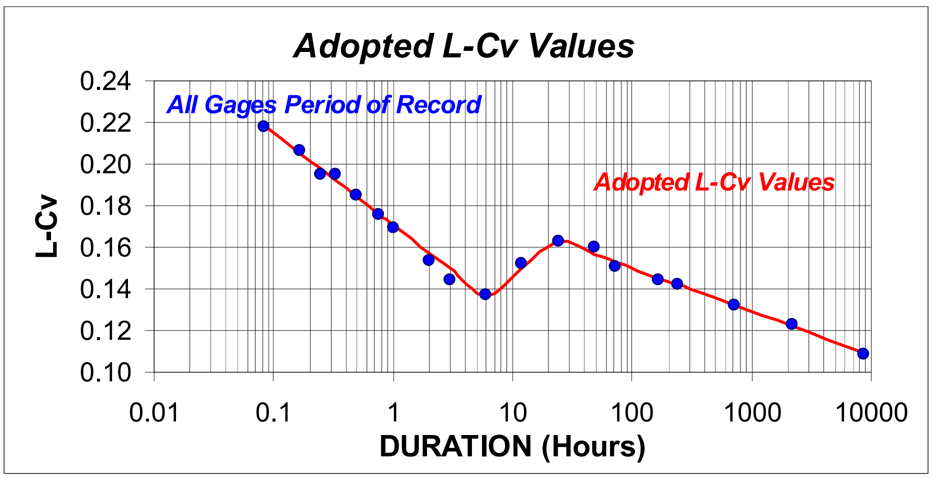


Figure 5 – Adopted Values of L-Cv for Durations of 5-Minutes through 7-Days

A comparison of Figures 6a and 6b shows that the adopted values of L-skewness (Figure 6b) for durations of 24-hours and greater are essentially the same as those obtained from prior large scale regional studies (red circles, Figure 6a). Those regional studies utilized from 400 to 600 gages with from 15,000 to 20,000 station-years of record. It is only in sample-sizes this large that reliable estimates can be obtained for measures of skewness.

The shape of the upper portion of the curve was based, in-part, on the results of regional studies of the 2-hour and 6-hour durations, representing about 120 gages and 4,800 station-years of record. The curve for durations of 5-minutes to 60-minutes is based on observations world-wide that indicates increasing intensities with reduced duration for short-duration precipitation. For example, the world record rainfall for 1-minute is 1.23-inches recorded in Unionville, Maryland. Locally, 0.47-inch has been recorded in Olympia, WA in 5-minutes and 0.79-inches has been recorded in Skykomish, WA in 10-minutes. These events reflect the volatility of very short-duration convective precipitation. Large values of L-skewness are needed to fit data that show this level of volatility. It should be noted that statistical analysis alone is insufficient to establish the relationship of L-skewness with duration for the shortest durations. Judgment is required in putting together the information presented above and developing a reasonable estimate of the relationship between L-skewness and duration.

As a practical matter, the differences in L-skewness values between the adopted values shown in Figure 6b (Table 2) and the sample values (blue diamonds) only starts to make a notable difference at return periods exceeding 100-years. In summary, the adopted values are judged to be nearer reality than the values from the small sample sizes available from the 17 gage network.

Table 2 – Observed L-Cv and L-Skewness Values and Adopted L-Cv and L-Skewness Values for the Seattle Metropolitan Area

DURATION	ALL GAGES 1965-2003		ALL GAGES PERIOD OF RECORD		ADOPTED VALUES	
	OBSERVED L-Cv	OBSERVED L-Skewness	OBSERVED L-Cv	OBSERVED L-Skewness	L-Cv	L-Skewness
5-MIN	0.2182	0.2574	0.2182	0.2574	0.2185	0.2700
10-MIN	0.2064	0.2113	0.2064	0.2113	0.2050	0.2650
15-MIN	0.1949	0.2318	0.1949	0.2318	0.1975	0.2600
20-MIN	0.1950	0.2168	0.1950	0.2168	0.1920	0.2550
30-MIN	0.1852	0.2146	0.1852	0.2146	0.1840	0.2500
45-MIN	0.1758	0.2288	0.1758	0.2288	0.1760	0.2450
60-MIN	0.1717	0.2410	0.1694	0.2365	0.1705	0.2400
2-HR	0.1550	0.2173	0.1535	0.2204	0.1575	0.2200
3-HR	0.1447	0.1894	0.1443	0.2043	0.1500	0.2100
6-HR	0.1383	0.1393	0.1371	0.1539	0.1365	0.1850
12-HR	0.1560	0.1864	0.1518	0.1837	0.1500	0.1800
24-HR	0.1689	0.2215	0.1625	0.2061	0.1630	0.1865
48-HR	0.1734	0.1478	0.1601	0.1683	0.1565	0.1950
72-HR	0.1652	0.1482	0.1508	0.1751	0.1530	0.1850
7-DAY	0.1592	0.0788	0.1444	0.1274	0.1450	0.1400

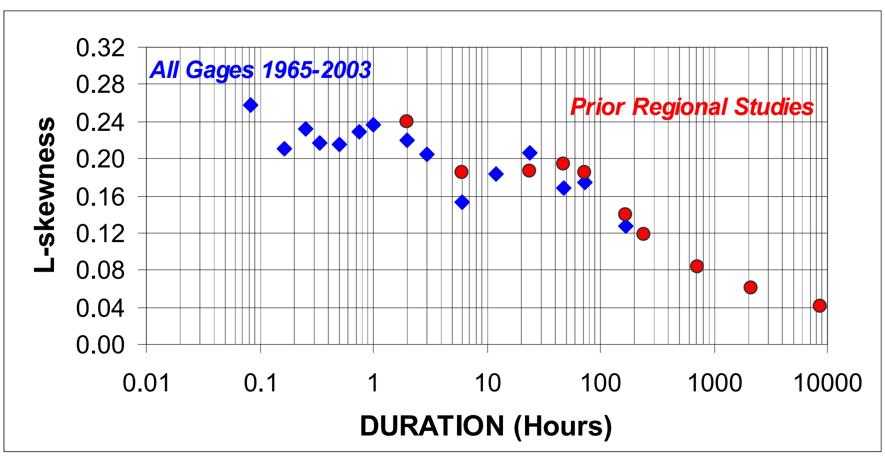


Figure 6a – Comparison of Regional L-skewness Values for 1965-2003 Period and Regional L-skewness Values from Prior Precipitation-Frequency Studies

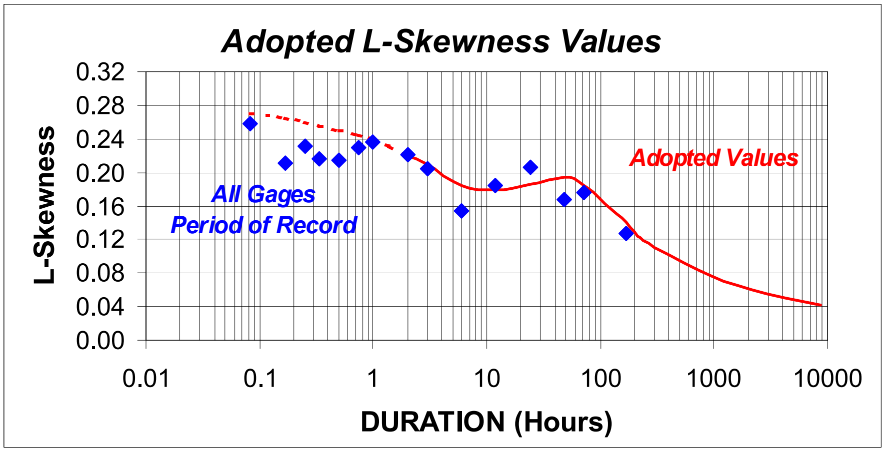


Figure 6b – Observed L- Skewness for Period of Record and Adopted Values of L-Skewness for Durations of 5-Minutes through 7-Days

Regional Probability Distribution Identification

A probability distribution is needed for describing the precipitation magnitude-frequency relationship for any site/gage within a homogeneous region. Probability distribution identification is typically accomplished using a goodness-of-fit test statistic. A goodness-of-fit test statistic has been developed by Hosking and Wallis[6] specifically for application with regional data. Their goodness-of-fit test statistic was used to identify the best three-parameter probability distribution to be used for each duration. Using this L-moment based test statistic, the three-parameter Generalized Extreme Value (GEV)[6,22] distribution was identified most frequently as the best three-parameter probability model.

L-skewness and L-kurtosis plots are a convenient way to display the observed L-moment ratio values with values for different probability distributions. L-skewness and L-kurtosis relationships are shown in Figure 7 for several three-parameter probability distributions. These include the Generalized Pareto, Generalized Logistic, Generalized Extreme Value, and Gamma distributions[5]. A plot of regional L-Skewness and regional L-Kurtosis values for the 15 durations is shown in Figure 7. It is seen that the L-moment ratio data tend to cluster around the GEV distribution. This behavior is consistent with the findings of other regional precipitation-frequency studies in the Northwest that determined the GEV distribution was the best distribution for describing precipitation annual maxima data (Schaefer[16,17,19]).

The inverse form of the GEV distribution for κ other than zero is:

$$p(F) = \xi + \frac{\alpha}{\kappa}\left\{1 - \left(-LN\left(F\right)\right)^{\kappa}\right\} \qquad (3)$$

where: $p(F)$ is the regional growth curve (regional inverse cumulative distribution function), ξ, α, and κ are location, scale and shape parameters, respectively.

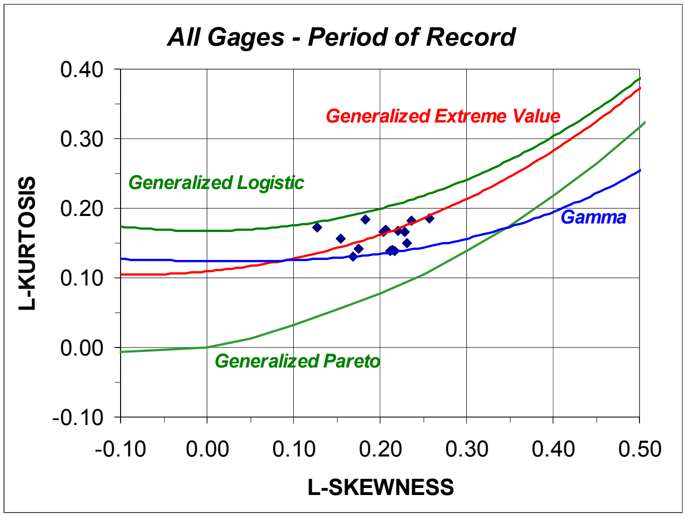


Figure 7 – L-Moment Ratio Plot of Durations from 5-Minutes through 7-Days
for All Gages for Period of Record

Distribution Parameters

The distribution parameters and conventional population product moments were determined based on a L-moments solution of the distribution parameters (Hosking and Wallis[6]). Table 3 lists the adopted values of the regional L-moment ratios, population moment ratios, and the GEV distribution parameters for the regional growth curves.

As discussed earlier, L-moments are a recently developed system for describing the shapes of probability distributions, computing sample statistics, and fitting of distribution parameters to observed data (Hosking[5,6]). Most readers will likely be unfamiliar with L-moments and thus, values of standard product-moment ratios of the coefficients of variation and skewness will be more familiar. Accordingly, both dimensionless measures of variance (L-Cv and Cv) and dimensionless measures of skewness (L-skewness and the coefficient of skewness) are listed in Table 3. They have some equivalence in that the distribution parameters listed in Table 3 produce the population moment ratio values in the two systems of measurement.

Table 3 – GEV Distribution Parameters and Population Moment Ratios
for Durations from 5-Minutes through 7-Days for the Seattle Metropolitan Area

DURATION	REGIONAL L-MOMENT RATIOS		POPULATION PRODUCT-MOMENT RATIOS		GEV DISTRIBUTION PARAMETERS		
	L-Cv	L-Skewness	Coefficient Variation Cv	Coefficient Skewness γ	Location ξ	Scale α	Shape κ
5-MIN	0.2185	0.2700	0.441	2.53	0.7985	0.2688	-0.1502
10-MIN	0.2050	0.2650	0.411	2.43	0.8118	0.2544	-0.1429
15-MIN	0.1975	0.2600	0.394	2.32	0.8195	0.2472	-0.1357
20-MIN	0.1920	0.2550	0.381	2.23	0.8253	0.2423	-0.1284
30-MIN	0.1840	0.2500	0.363	2.14	0.8333	0.2342	-0.1211
45-MIN	0.1760	0.2450	0.346	2.06	0.8413	0.2259	-0.1137
60-MIN	0.1705	0.2400	0.333	1.98	0.8470	0.2207	-0.1064
2-HR	0.1575	0.2200	0.302	1.69	0.8614	0.2105	-0.0767
3-HR	0.1500	0.2100	0.285	1.56	0.8694	0.2037	-0.0616
6-HR	0.1365	0.1850	0.255	1.29	0.8844	0.1925	-0.0236
12-HR	0.1500	0.1800	0.279	1.24	0.8737	0.2131	-0.0159
24-HR	0.1630	0.1865	0.305	1.30	0.8617	0.2294	-0.0259
48-HR	0.1565	0.1950	0.295	1.39	0.8659	0.2175	-0.0389
72-HR	0.1530	0.1850	0.286	1.29	0.8704	0.2158	-0.0236
7-DAY	0.1450	0.1400	0.264	0.88	0.8840	0.2180	+0.0469

At-Site Precipitation Magnitude-Frequency Curves

At-site precipitation magnitude-frequency curves are produced as the product of the at-site mean and the regional growth curve (Equations 1, 2a, 2b, 3, Table 3). Examples of probability-plots of observed annual maxima along with the regional solution for the precipitation magnitude-frequency curves are depicted in Figures 8a,b,c,d; 9a,b,c; 10a,b,c; and 11,a,b,c; for various durations at SPU gages 1, 3, 11 and 15.

Sampling variability and gage-specific differences due to calibration, level of maintenance and gage setting/exposure are the primary factors that account for the differences between observed at-site and regional-average behavior. The general goodness-of-fit between the observed and predicted values can be seen in the various probability-plots.

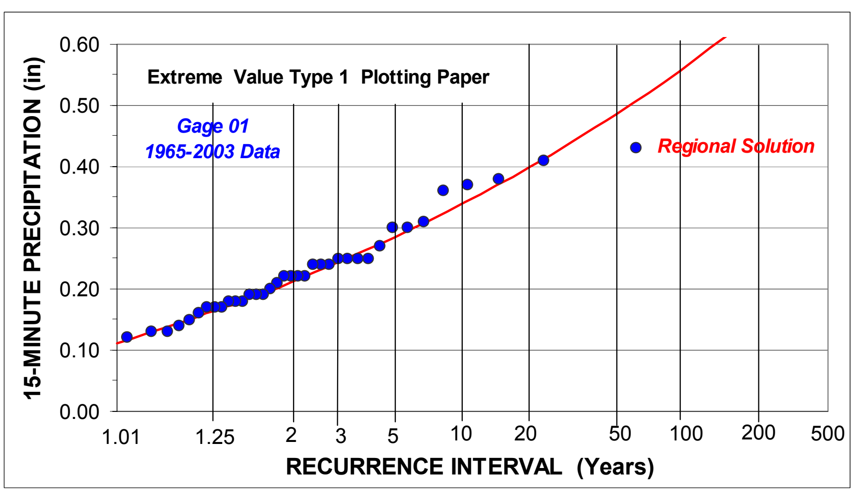


Figure 8a – Probability-Plot of Observed 15-Minute Annual Maxima
and Regional Precipitation-Frequency Curve for Haller Lake Shop (SPU Gage 01)

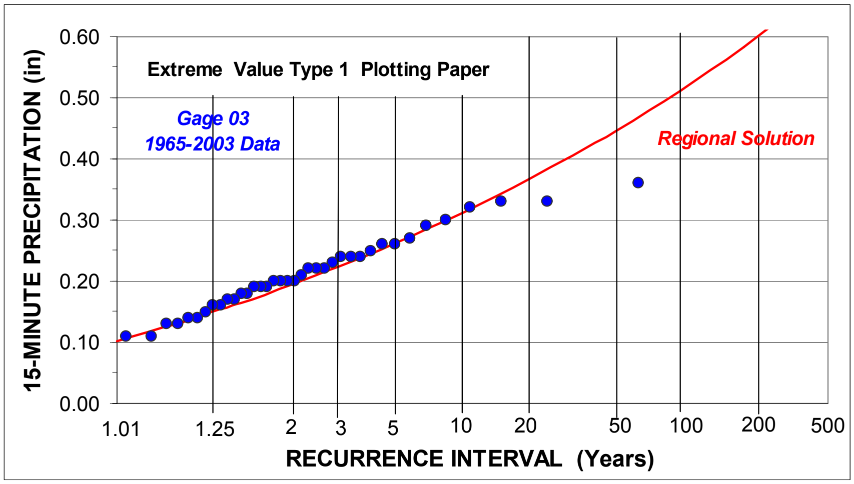


Figure 8b – Probability-Plot of Observed 15-Minute Annual Maxima and Regional Precipitation-Frequency Curve for UW Hydraulics Laboratory (SPU Gage 03)

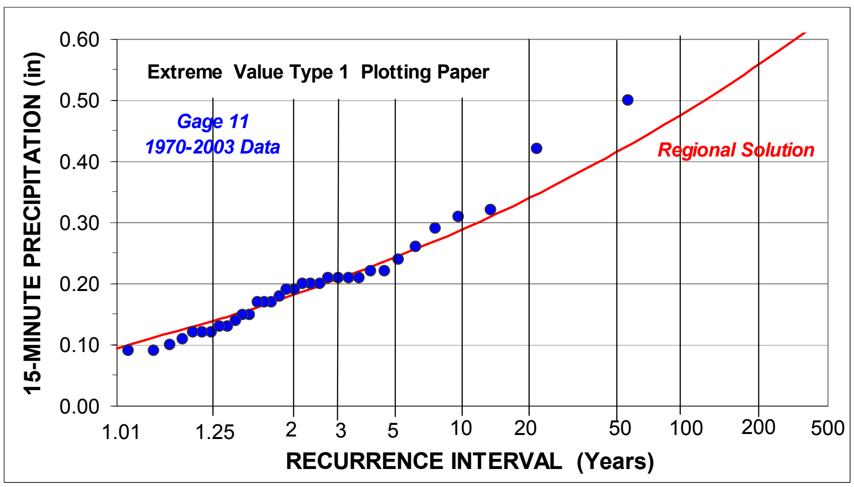


Figure 8c – Probability-Plot of Observed 15-Minute Annual Maxima and Regional Precipitation-Frequency Curve for Metro KC Denny Regulator (SPU Gage 11)

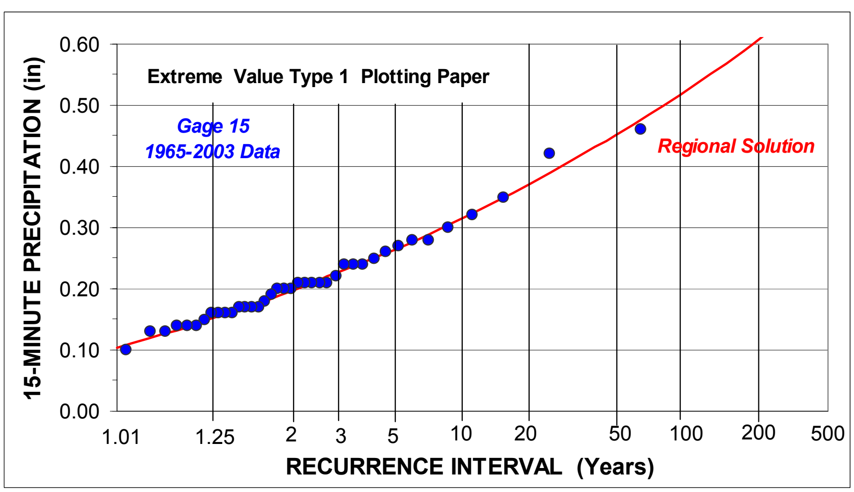


Figure 8d – Probability-Plot of Observed 15-Minute Annual Maxima and Regional Precipitation-Frequency Curve for Metro KC Diagonal Pump Station (SPU Gage 15)

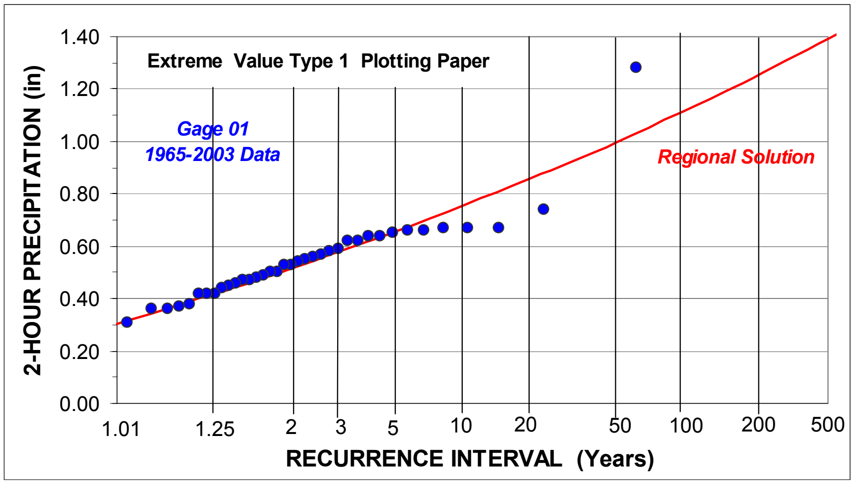


Figure 9a – Probability-Plot of Observed 2-Hour Annual Maxima
and Regional Precipitation-Frequency Curve for Haller Lake Shop (SPU Gage 01)

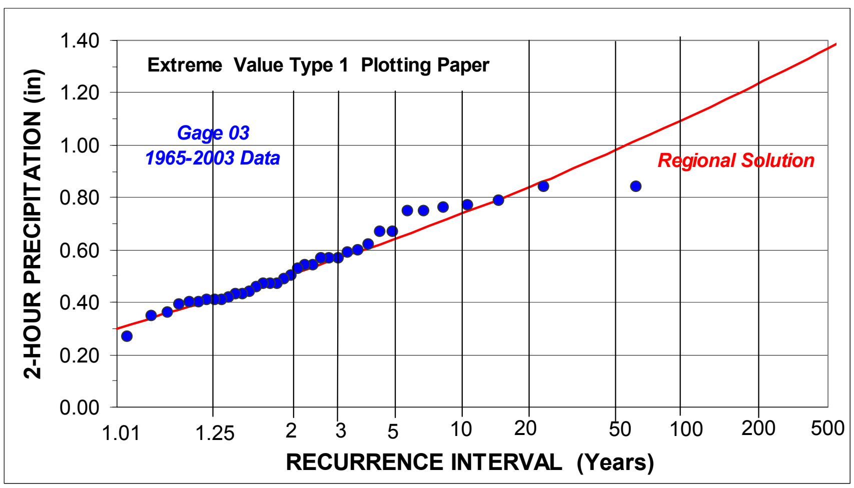


Figure 9b – Probability-Plot of Observed 2-Hour Annual Maxima
and Regional Precipitation-Frequency Curve for UW Hydraulics Laboratory (SPU Gage 03)

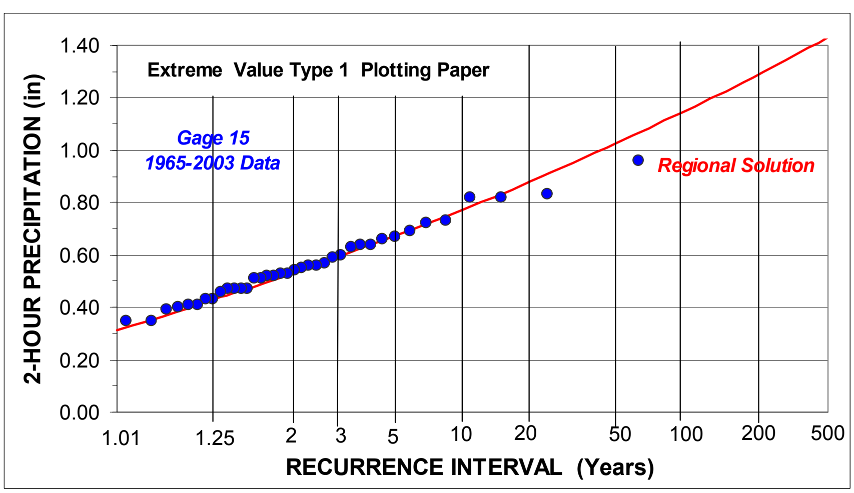


Figure 9c – Probability-Plot of Observed 2-Hour Annual Maxima and
Regional Precipitation-Frequency Curve for Metro KC Diagonal Pump Station (SPU Gage 15)

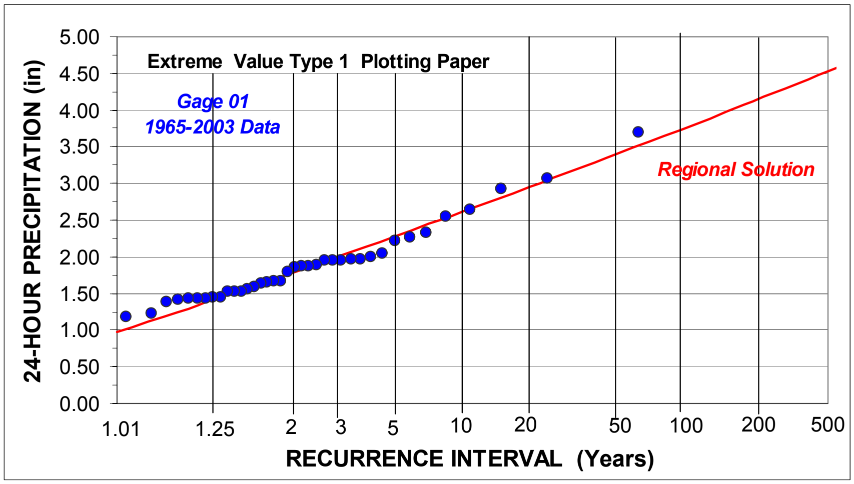


Figure 10a – Probability-Plot of Observed 24-Hour Annual Maxima
and Regional Precipitation-Frequency Curve for Haller Lake Shop (SPU Gage 01)

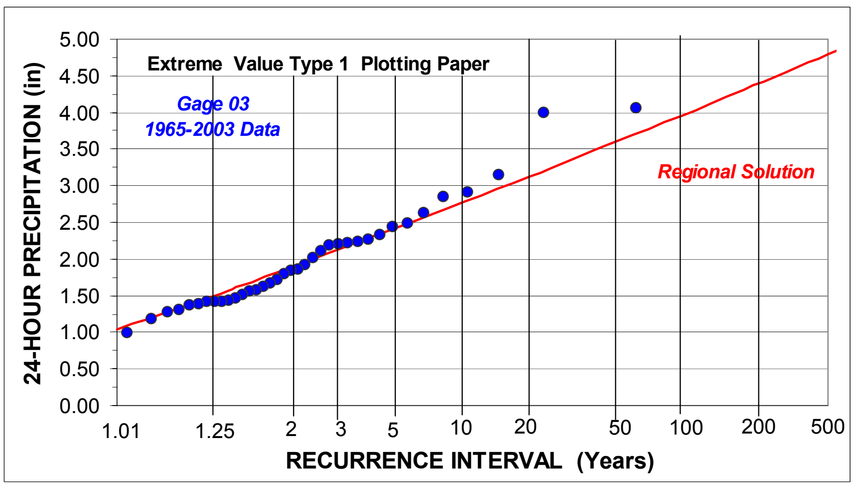


Figure 10b – Probability-Plot of Observed 24-Hour Annual Maxima
and Regional Precipitation-Frequency Curve for UW Hydraulics Laboratory (SPU Gage 03)

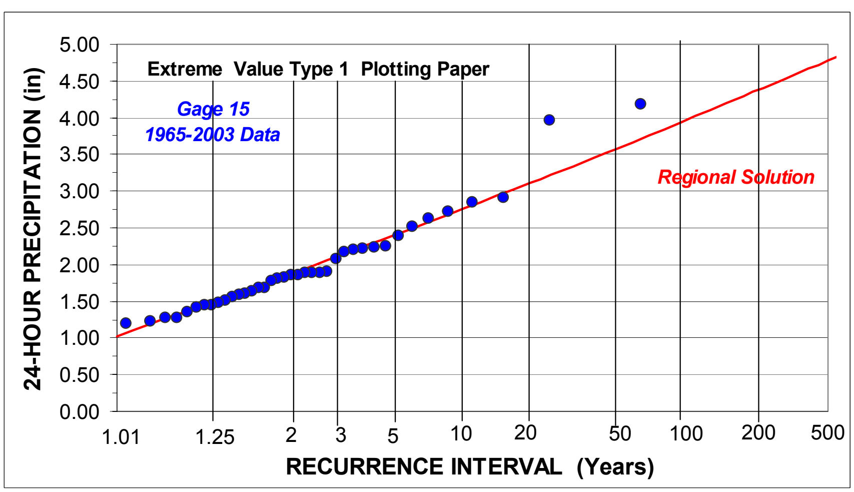


Figure 10c – Probability-Plot of Observed 24-Hour Annual Maxima and
Regional Precipitation-Frequency Curve for Metro KC Diagonal Pump Station (SPU Gage 15)

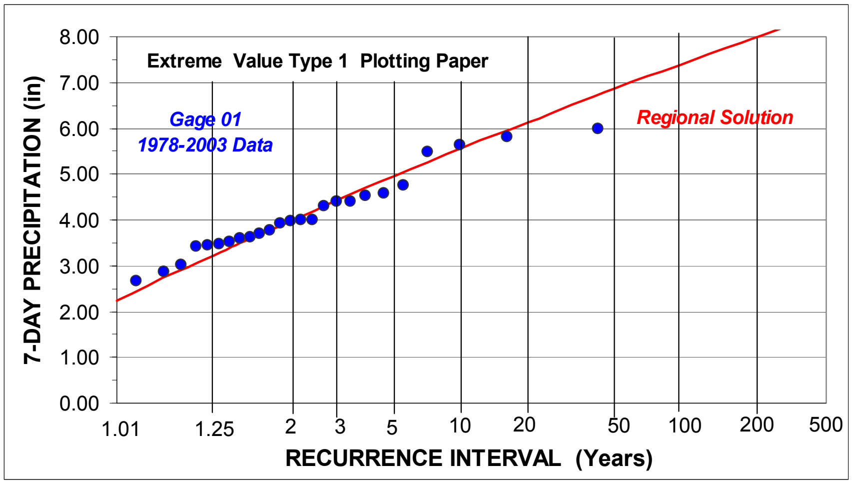


Figure 11a – Probability-Plot of Observed 7-Day Annual Maxima
and Regional Precipitation-Frequency Curve for Haller Lake Shop (SPU Gage 01)

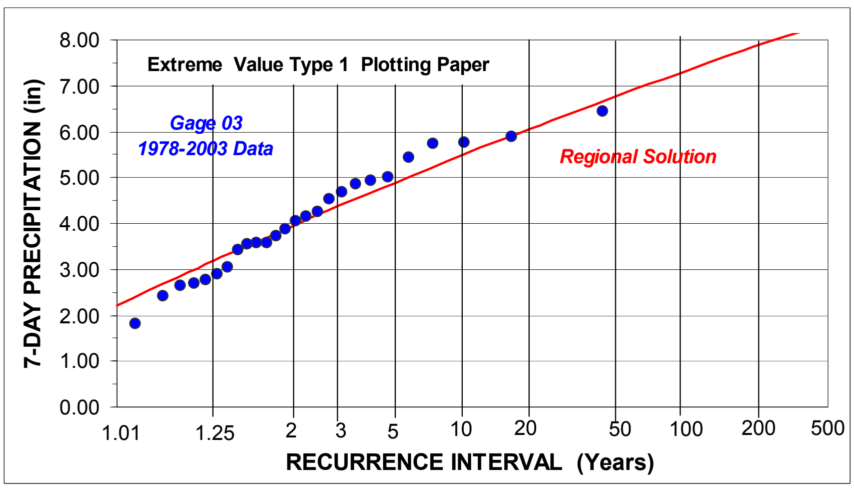


Figure 11b – Probability-Plot of Observed 7-Day Annual Maxima
and Regional Precipitation-Frequency Curve for UW Hydraulics Laboratory (SPU Gage 03)

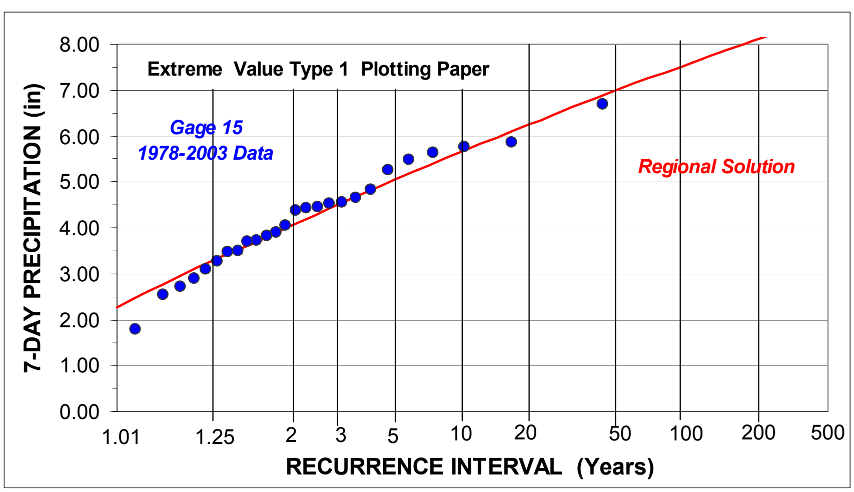


Figure 11c – Probability-Plot of Observed 7-Day Annual Maxima and
Regional Precipitation-Frequency Curve for Metro KC Diagonal Pump Station (SPU Gage 15)

Precipitation Magnitude-Frequency Curves for Sea-Tac Airport

Precipitation data from the gage at Sea-Tac Airport have long been used as a benchmark for precipitation characteristics in the Seattle area. Therefore, it is logical to compare the findings of the regional precipitation-frequency analysis with the annual maxima data from the Sea-Tac gage.

Probability-plots for the Sea-Tac Airport are depicted in Figures 12a,b,c,d. For any given duration, the shape of the precipitation magnitude-frequency curve (regional growth curve) is the same for Sea-Tac as for the other gages/sites in the homogeneous region that includes the Seattle Metropolitan area. Differences in the magnitude-frequency curves between Sea-Tac and the Seattle Metropolitan area for durations of 6-hours and greater are due to the heterogeneity of precipitation characteristics. Specifically, precipitation magnitudes for a given recurrence interval slowly decrease in magnitude in progressing from southwest to northeast across the Seattle Metropolitan Area. Precipitation magnitudes begin to increase to the east of the City due to the orographic influence of the Cascade Mountains.

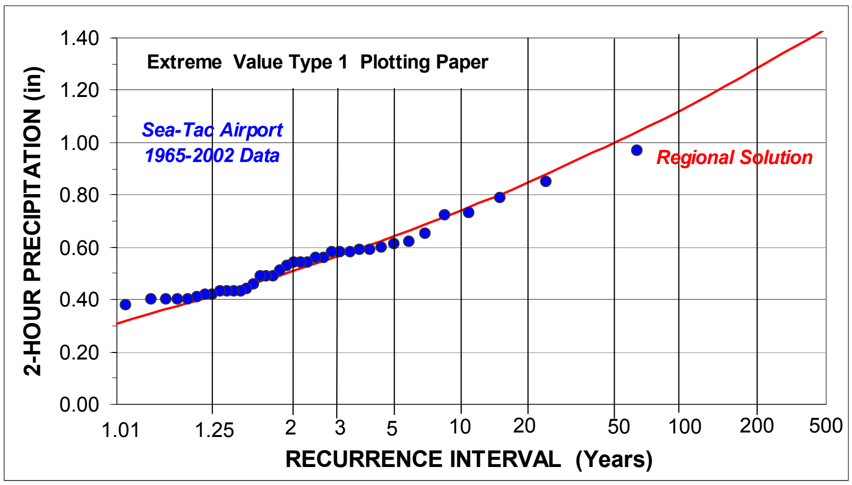


Figure 12a – Probability-Plot of Observed 2-Hour Annual Maxima and Regional Precipitation-Frequency Curve for Sea-Tac Airport

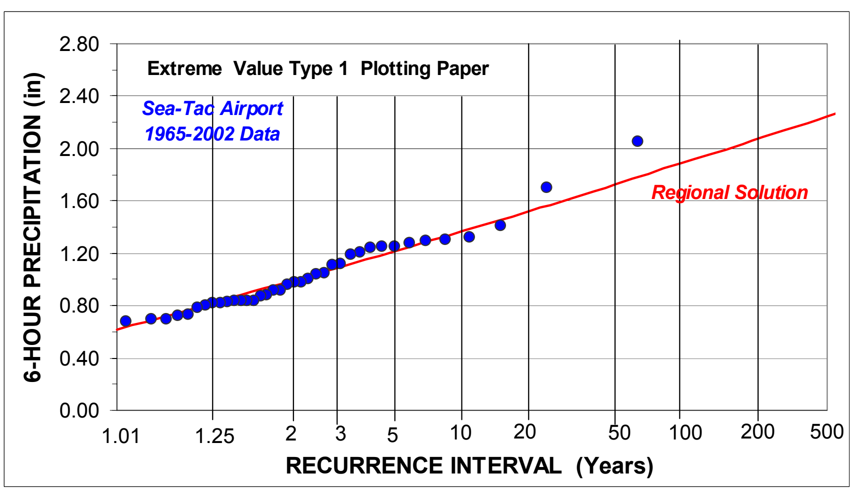


Figure 12b – Probability-Plot of Observed 6-Hour Annual Maxima and Regional Precipitation-Frequency Curve for Sea-Tac Airport

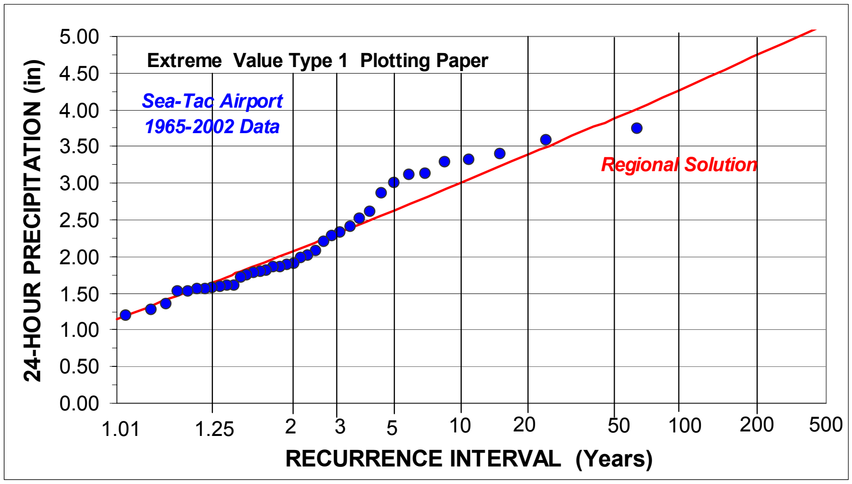


Figure 12c – Probability-Plot of Observed 24-Hour Annual Maxima and Regional Precipitation-Frequency Curve for Sea-Tac Airport

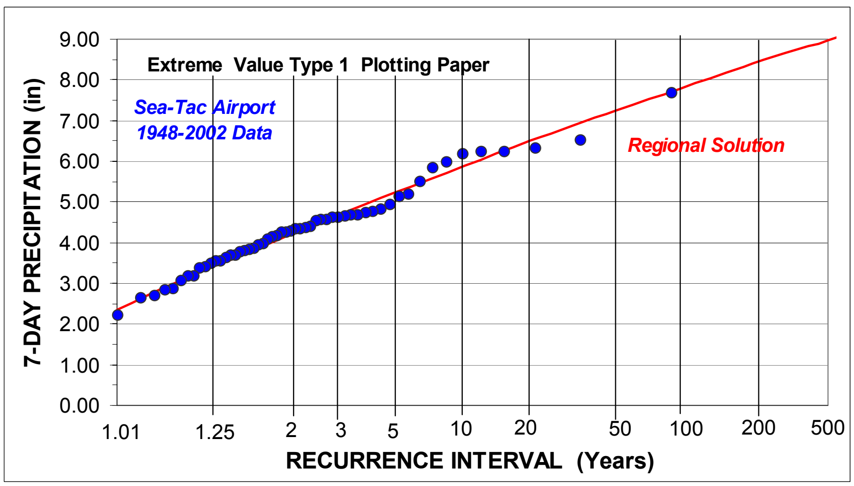


Figure 12d – Probability-Plot of Observed 7-Day Annual Maxima and Regional Precipitation-Frequency Curve for Sea-Tac Airport

Magnitude-Frequency of Common Storm Events

Annual maxima series datasets have been shown to be the most robust approach to data collection for use in regional frequency analysis (Hosking[6], Stedinger[22]). Annual maxima series are particularly well-suited to estimation of rare events with recurrence intervals of 50-years and greater. Conversely, partial duration series datasets are better suited to estimation of events that occur several times each year. Partial duration series are assembled by including all events that exceed some threshold, where the threshold is chosen sufficiently low to include all events of possible interest. When using annual maxima series datasets, estimation of the frequency of common events is accomplished by adjustments of the recurrence intervals to produce equivalence with a partial duration series analysis. This was accomplished in this study using an equation developed by Langbein[9] for the intensity-duration-frequency curves and for the magnitude-frequency curves presented in Appendix E:

$$RI_{pds} = [-LN(1 - 1/RI_{ams})]^{-1} \qquad (4)$$

where: RI_{pds} is the recurrence interval for the partial duration series (years); and RI_{ams} is the recurrence interval for the annual maxima series (years).

HOMOGENEITY OF PRECIPITATION FOR SEATTLE METROPOLITAN AREA

Examination of precipitation homogeneity within the city limits was identified as a high priority by SPU in developing the scope-of-work for this study. The term homogeneity has a variety of meanings as applied to precipitation analyses and precipitation characteristics. Homogeneity is a consideration in developing intensity-duration-frequency relationships and in developing design storms. It is also a consideration in conducting precipitation-frequency analyses and in transposing data from one site to another for fill-in of missing records. In each of these applications, homogeneity refers to some type or level of similarity/commonality of precipitation characteristics. However, the exact meaning and the conditions necessary to meet homogeneity criteria vary from application to application.

The meaning of homogeneity for each of the above applications is described in the following sections. These descriptions are intended to provide a framework for identifying how homogeneity applies to the various precipitation analyses that were conducted for the City of Seattle.

INTENSITY-DURATION-FREQUENCY RELATIONSHIPS

Homogeneity of intensity-duration-frequency (IDF) relationships refers to the similarity of IDF curves for various sites within a geographical area. Specifically, IDF curves within a homogeneous region must be sufficiently similar that one set of curves (Figure 13) would apply to all sites in the region.

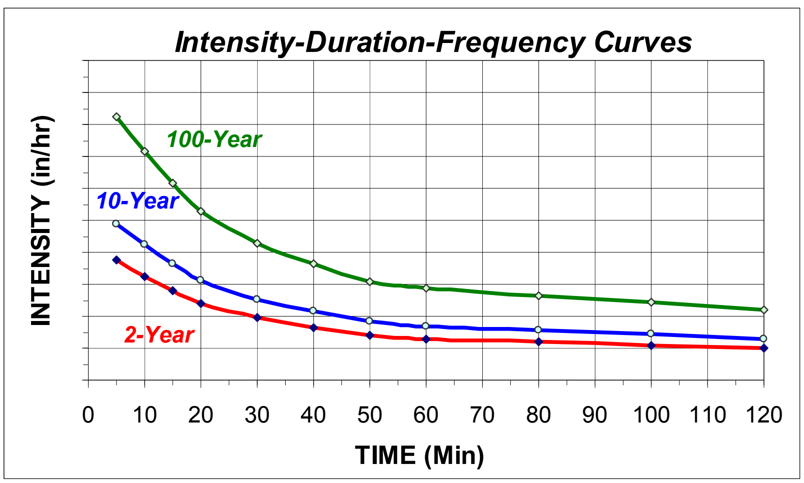


Figure 13 – Example of Intensity-Duration-Frequency Curves

Homogeneity of IDF curves requires that a single probability distribution with common distribution parameters be applicable to each of the durations used to describe the IDF curves. This can be viewed as each site within the homogeneous region having precipitation annual maxima data with common at-site mean, and coefficients of variation and skewness for each duration of interest.

Experience in conducting regional precipitation-frequency analyses in the Pacific Northwest (Schaefer[16,17,19]) has shown that similar values of the coefficients of variation and skewness commonly exist over geographic areas having similar topographic settings and climatic characteristics. Homogeneity tests were conducted (Hosking and Wallis[6]) to examine the variability of the coefficients of variation and skewness for each duration for the collection of precipitation gages. As expected, it was found that fixed values of the coefficients of variation and skewness were applicable to each of the 15 durations (see prior section on Precipitation Magnitude-Frequency.

The remaining criterion for homogeneity of IDF curves requires that all sites have common values of the at-site mean for each of the durations of interest. A review of precipitation isopluvial maps from prior studies (OCS[14], Schaefer et al[19]) shows precipitation magnitudes generally decreasing across the Seattle Metropolitan Area in a southwest to northeast orientation. The City of Seattle extends about 20-miles in the north-south direction and about 8-miles in the east-west direction. Therefore, variation in precipitation magnitudes across the City would be more apparent in the north-south direction. Accordingly, the homogeneity of at-site means was analyzed by examining the trend of the at-site mean values with latitude for all of the durations of interest. This analysis was conducted for the common period of record from 1965-2003. Specifically, the null hypothesis of a regression slope equal to zero was tested against the alternative that the regression slope was not equal to zero at the 95% confidence level. It was concluded that there was no trend of at-site mean values with latitude for the durations of 3-hours and shorter. A north-south trend becomes clearly apparent for durations of 12-hours and greater. This behavior is shown in Figures 14a,b,c,d,e for a range of durations. No significant trend was found for the narrow range of longitude within the City limits for any of the durations from 5-min through 7-days.

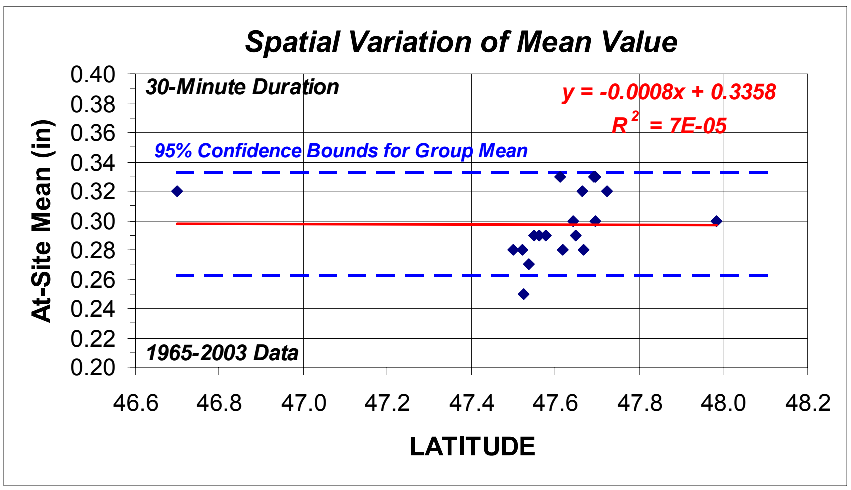


Figure 14a – Scatter-Plot of At-Site Mean Values with Latitude for 30-Minute Annual Maxima Precipitation

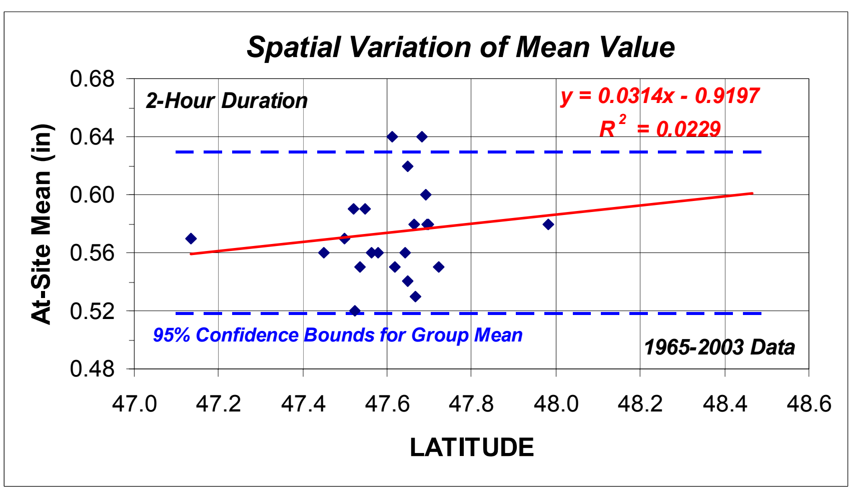


Figure 14b – Scatter-Plot of At-Site Mean Values with Latitude for 2-Hour Annual Maxima Precipitation

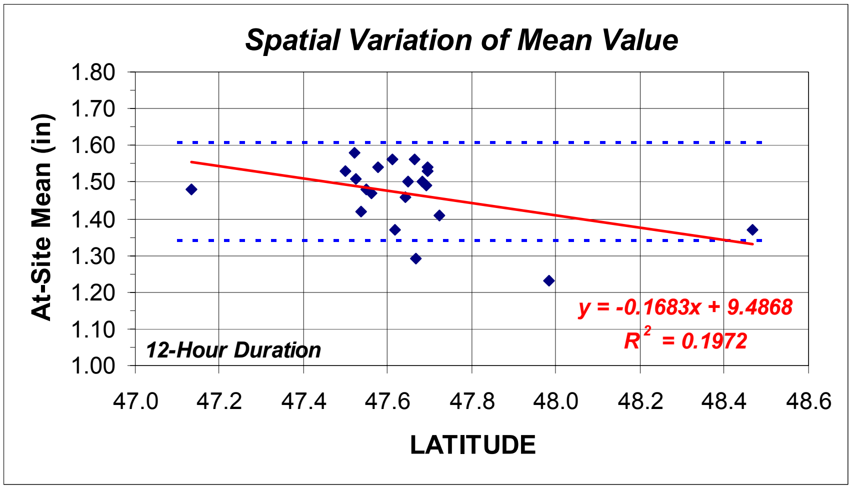


Figure 14c – Relationship of At-Site Mean Values with Latitude for 12-Hour Annual Maxima Precipitation

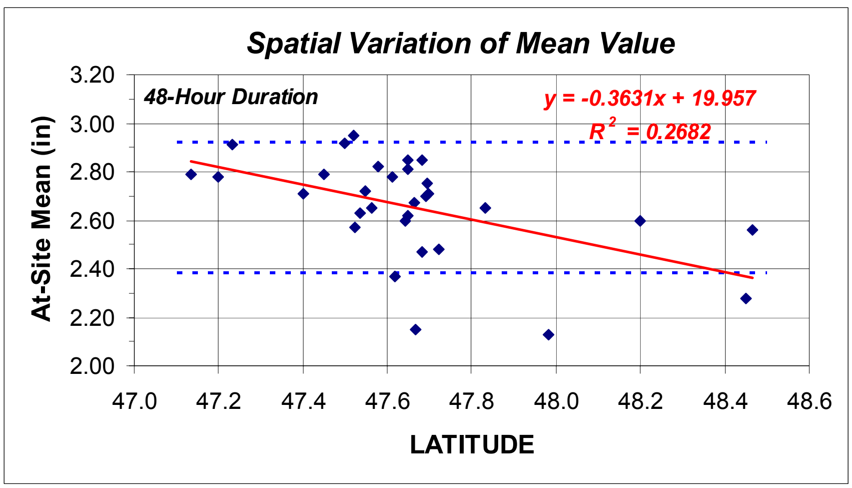


Figure 14d – Relationship of At-Site Mean Values with Latitude for 48-Hour Annual Maxima Precipitation

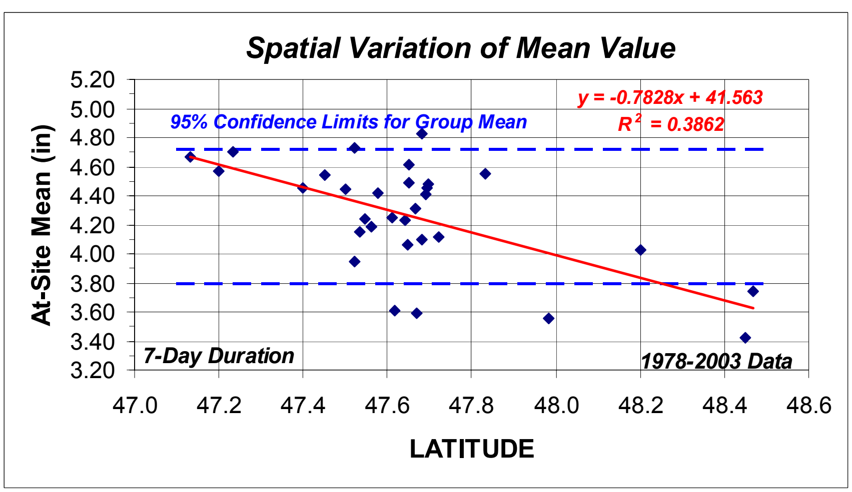


Figure 14e – Relationship of At-Site Mean Values with Latitude for 7-Day Annual Maxima Precipitation

Application of Homogeneity Findings for IDF Curves

The primary use of Intensity-Duration-Frequency curves is in application of the rational equation for estimating peak discharges from small urbanized areas. The assumptions used in deriving the rational equation results in the approach being most valid for very short durations of precipitation, perhaps 15-minutes and less. The suitability of the rational equation is diminished as the time-of-concentration for the drainage area increases. For example, King County[8] limits application of the rational equation to drainage areas less than 10-acres and to a time-of-concentration less than 100-minutes. For these reasons, the primary focus of the IDF curves is for durations of 100-minutes and less.

The results of the homogeneity analyses indicate that at-site mean values do not vary across the Seattle Metropolitan Area for durations of 3-hours and less. Accordingly, one set of IDF curves can be developed that are applicable to the Seattle Metropolitan Area. Table 4 lists the at-site mean values that were used with the regional magnitude-frequency relationships to describe the IDF curves. These group at-site mean values were obtained as weighted averages of the at-site mean values at the individual gages as weighted by record length for the period from 1965-2003. Minor adjustments (Weiss[24]) were made to the at-site mean values for the 5-minute to 30-minute durations for the time-series data from 1978-2003 to correct for small differences that occur due to reporting on 5-minute intervals rather than continuously.

Table 4 – Group At-Site Mean Values
for Developing Intensity-Duration-Frequency Curves

DURATION	GROUP AT-SITE MEAN
5-MIN	0.136-inch
10-MIN	0.186-inch
15-MIN	0.223-inch
20-MIN	0.251-inch
30-MIN	0.298-inch
45-MIN	0.352-inch
60-MIN	0.403-inch
2-HR	0.564-inch
3-HR	0.708-inch

Development of Intensity-Duration-Frequency Curves

Intensity-Duration-Frequency curves were developed for the Seattle Metropolitan Area by scaling the regional growth curve for each duration (Figure 2, Equation 1), by the at-site mean values shown in Table 4. Numerically, this was accomplished using Equations 2a, 2b, 3, and distribution parameter values for the GEV distribution listed in Table 3 for the durations from 5-minutes through 3-hours. The precipitation-frequency values are listed in Table 5 and graphically depicted in Figures 15a,b. Intensity-Duration-Frequency values expressed as precipitation depth (inches) are listed in Appendix F.

Table 5 – Intensity-Duration-Frequency Values for Durations from 5-Minutes through 180-Minutes for Selected Recurrence Intervals for the Seattle Metropolitan Area

DURATION (minutes)	PRECIPITATION INTENSITIES (in/hr)							
	RECURRENCE INTERVAL (Years)							
	6-Month	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
5	1.01	1.60	2.08	2.45	2.92	3.08	3.61	4.20
6	0.92	1.45	1.87	2.21	2.62	2.76	3.23	3.75
8	0.80	1.24	1.59	1.87	2.21	2.32	2.71	3.13
10	0.71	1.10	1.40	1.64	1.93	2.03	2.36	2.72
12	0.65	1.00	1.27	1.48	1.74	1.82	2.11	2.43
15	0.58	0.88	1.12	1.30	1.52	1.60	1.84	2.11
20	0.50	0.75	0.95	1.10	1.28	1.34	1.54	1.76
25	0.45	0.67	0.84	0.97	1.12	1.18	1.35	1.53
30	0.41	0.61	0.76	0.87	1.01	1.05	1.21	1.37
35	0.38	0.56	0.69	0.80	0.92	0.96	1.10	1.24
40	0.35	0.52	0.64	0.74	0.85	0.89	1.01	1.14
45	0.33	0.49	0.60	0.69	0.79	0.83	0.94	1.06
50	0.32	0.46	0.57	0.65	0.74	0.78	0.88	0.99
55	0.30	0.44	0.54	0.61	0.70	0.73	0.83	0.94
60	0.29	0.42	0.51	0.58	0.67	0.70	0.79	0.89
65	0.28	0.40	0.49	0.56	0.64	0.66	0.75	0.84
70	0.27	0.38	0.47	0.53	0.61	0.64	0.72	0.80
80	0.25	0.36	0.43	0.49	0.56	0.59	0.66	0.74
90	0.24	0.33	0.41	0.46	0.52	0.55	0.62	0.69
100	0.22	0.32	0.38	0.43	0.49	0.51	0.58	0.64
120	0.20	0.29	0.35	0.39	0.44	0.46	0.52	0.57
140	0.19	0.26	0.32	0.36	0.40	0.42	0.47	0.52
160	0.18	0.24	0.29	0.33	0.37	0.39	0.43	0.48
180	0.17	0.23	0.27	0.31	0.35	0.36	0.40	0.45

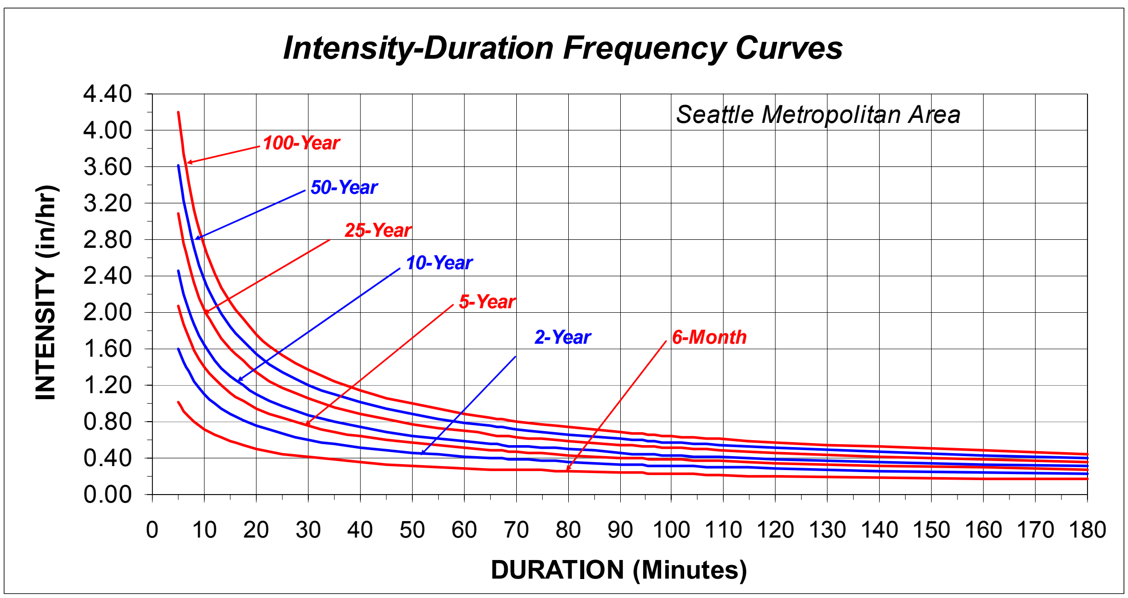


Figure 15a – Intensity-Duration-Frequency Curves for the Seattle Metropolitan Area

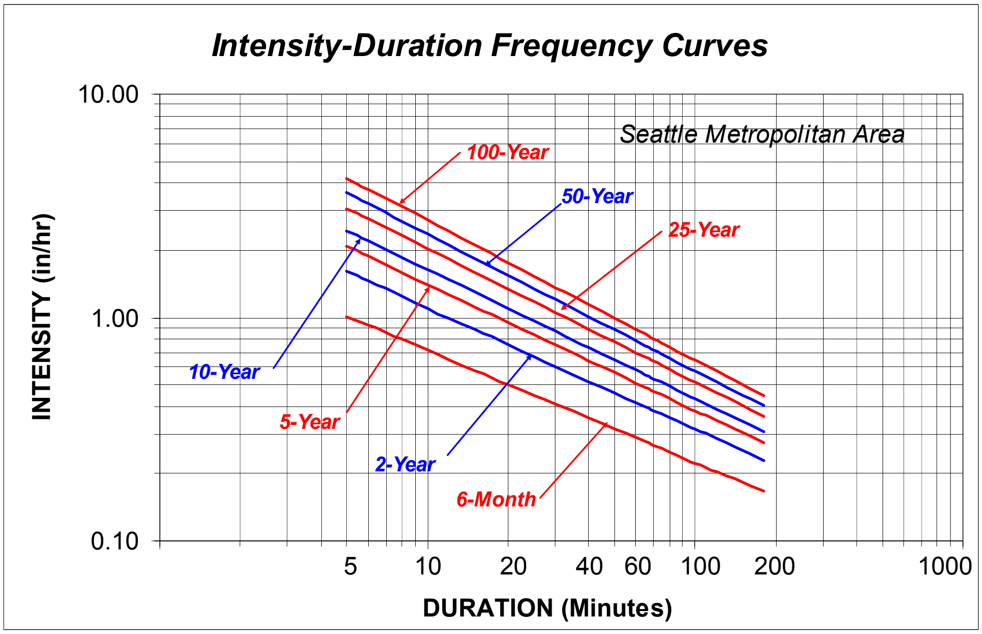


Figure 15b – Intensity-Duration-Frequency Curves for the Seattle Metropolitan Area

SPATIAL DISTRIBUTION OF 6-HOUR THROUGH 7-DAY PRECIPITATION

Homogeneity of at-site means was examined in the prior section. From those analyses it was concluded that the Seattle Metropolitan Area was heterogeneous regarding at-site mean values for durations of 6-hours and greater. Heterogeneity of the at-site means results in variation of precipitation-frequency values across the City of Seattle for durations of 6-hours and greater. The existence of this heterogeneity requires that the spatial distribution of precipitation be described for durations of 6-hr, 12-hr, 24-hr, 48-hr, 72-hr and 7-days.

Description of the spatial distribution of precipitation across the City is accomplished by developing gridded datasets of at-site mean values for each of the various durations. These gridded at-site mean datasets may then be used with the appropriate regional growth curve for each duration (Figure 2), Equations 2a, 2b, and 3 and distribution parameter values for the GEV distribution (Table 4), to developed gridded precipitation datasets for any selected recurrence interval for a given duration. These gridded datasets can then be used in GIS applications for preparing precipitation-frequency isopluvial maps.

Gridded datasets are provided in ASCII text files on a compact disc (CD) that is included as part of the deliverables for this project. They may be viewed with any standard electronic text editor. They may also be imported into any standard electronic spreadsheet or converted to a raster file for importing into spatial mapping software such as *ArcGIS* by ESRI.

Gridded Dataset for 24-Hour At-Site Mean Values

Gridded datasets of the at-site mean values were developed in several steps. First, a comparison was made between the observed values of the 24-hour at-site means for the collection of gages (Tables 1a,b,c) and corresponding values of the 24-hour at-site means contained within the WSDOT[19] 24-hour gridded dataset for the gage locations (Figure 16). The results of this comparison are shown in Figure 17 and demonstrate good agreement between the observed 24-hour at-site means and mapped WSDOT 24-hour values. With the exception of one SPU gage, differences between the two datasets are within the error bounds normally attributable to sampling variability and measurement, recording, and calibration errors associated with precipitation data. The WSDOT 24-hour at-site mean map (Figure 16) was accepted as representative of the Seattle area.

Compatibility of results was anticipated because the WSDOT map[19] was developed using over 100 precipitation gages within the Puget Sound Lowlands including about one dozen gages within or near the City of Seattle.

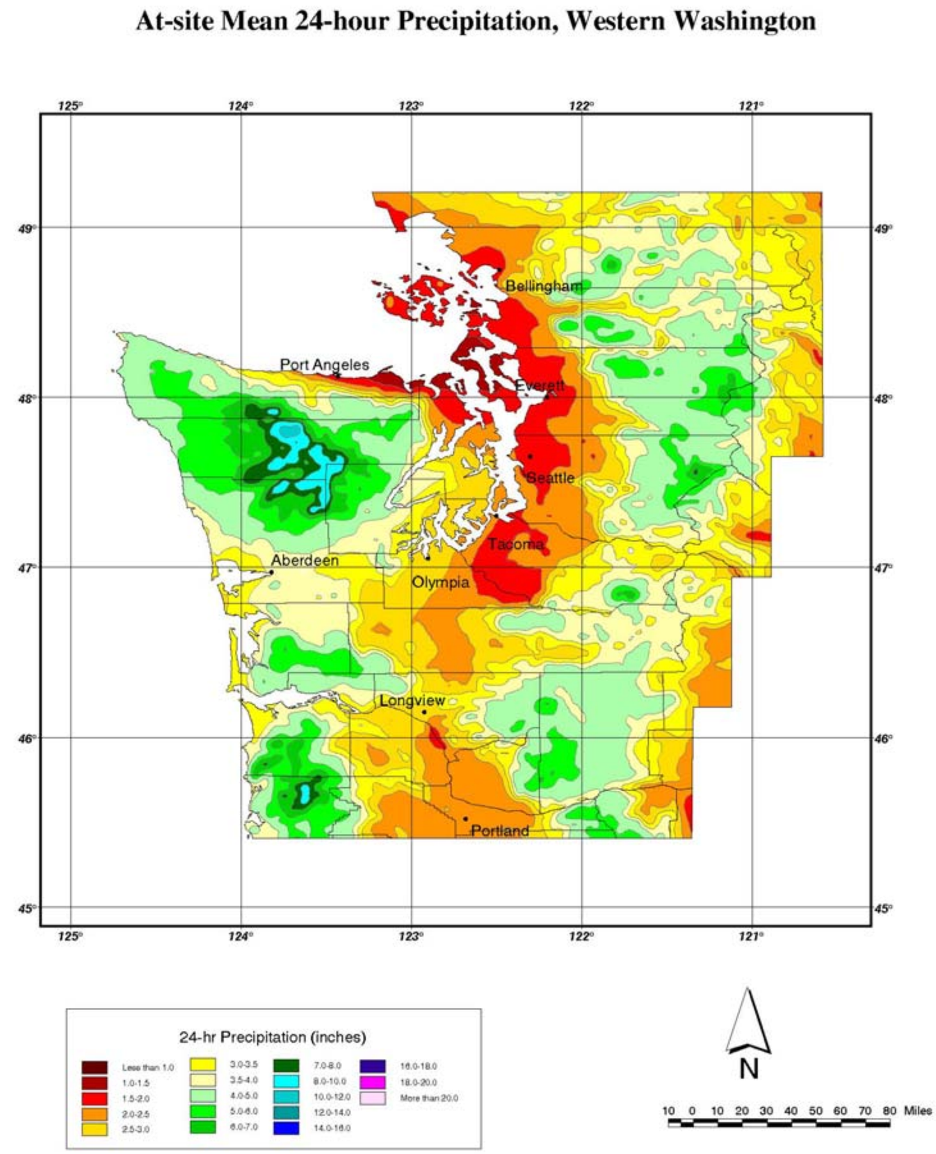


Figure 16 – Map of 24-Hour At-Site Mean Values for Western Washington Obtained from 2002 WSDOT Study[19]

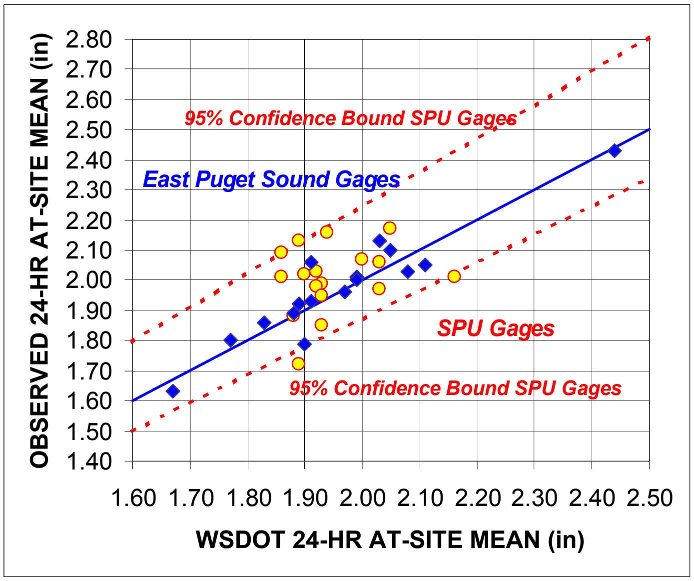


Figure 16 – Comparison of Observed 24-Hour At-Site Mean Values with WSDOT Mapped Values of 24-Hour At-Site Means

Gridded Datasets for 6-Hour, 12-Hour, 48-Hour, 72-Hour and 7-Day At-Site Mean Values

Gridded datasets of at-site mean values for durations other than 24-hours were developed by linear correlation of the observed at-site mean values for a given duration and 24-hour at-site mean values from the WSDOT gridded dataset (Figure 16). Numerically:

$$Mean_{nhour} = \alpha + \beta\, Mean_{24hour} \tag{5}$$

where: $Mean_{nhour}$ is the at-site mean value for some duration of interest; α and β are intercept and slope parameters for the linear regression solution, respectively; and $Mean_{24hour}$ is the WSDOT[19] at-site mean value for the 24-hour duration for a grid-cell location.

This approach recognizes the general similarity of the spatial distribution of precipitation amongst the various durations and explicitly incorporates the observed measurements to produce the gridded dataset for a given duration. Examples of the correlation relationships are depicted in Figures 17a,b. Much of the scatter in the data in Figures 17a,b is attributable to sampling variability, and measurement, recording, and calibration errors rather than real site-to-site variations.

The parameters of the linear regression relationships are listed in Table 6 along with measures of the standard error of estimation. A review of the standard errors of estimation shows values near 7% and less, which are within the bounds expected due to sampling variability, and measurement, recording, and calibration errors commonly associated with precipitation data.

The WSDOT[19] gridded-data set of 24-hour at-site mean values has a nominal grid-cell size of 2-km. This equates to 1.25 minutes of longitude-latitude or a matrix of 48x48 grid-cells per degree of latitude-longitude. Spatial interpolation was conducted on all gridded datasets to produce high resolution datasets on a matrix of 480x480 grid-cells (230,400 grid-cells) per degree of latitude-longitude suitable for construction of color-shaded maps.

Table 6 – Linear Regression Parameters for Relationship Between 24-Hour At-Site Mean Values and At-Site Mean Values at Other Durations for Seattle Metropolitan Area

DURATION	LINEAR REGRESSION PARAMETERS			STANDARD ERROR OF ESTIMATION
	INTERCEPT (α)	SLOPE (β)	CORRELATION COEFFICIENT (ρ)	
6-HOUR	0.604	0.214	0.653	4.6%
12-HOUR	0.487	0.509	0.575	5.1%
24-HOUR	From WSDOT[16] Study			4.4%
48-HOUR	0.340	1.190	0.844	6.9%
72-HOUR	0.076	1.514	0.893	7.3%
7-DAY	-0.655	2.546	0.846	6.3%

Color-shaded maps of the at-site mean gridded datasets are shown in Figures 18a,b,c,d,e,f for the durations from 6-hours to 7-days. Comparison of the six figures shows the greatest variation in at-site mean values occurs at the 7-day duration, and there is little difference in 6-hour at-site means across the Seattle Metropolitan Area. Thus, precipitation magnitudes show increased spatial variability with duration.

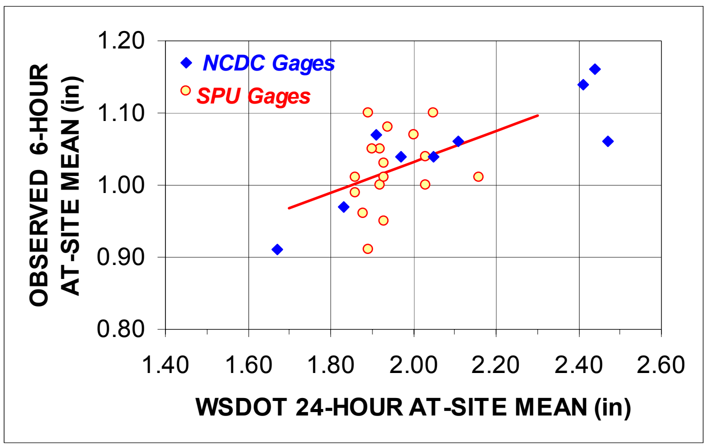


Figure 17a – Relationship Between Observed 6-Hour At-Site Mean Values and 24-Hour At-Site Mean Values from WSDOT[19] Gridded Dataset for Location of Precipitation Gages

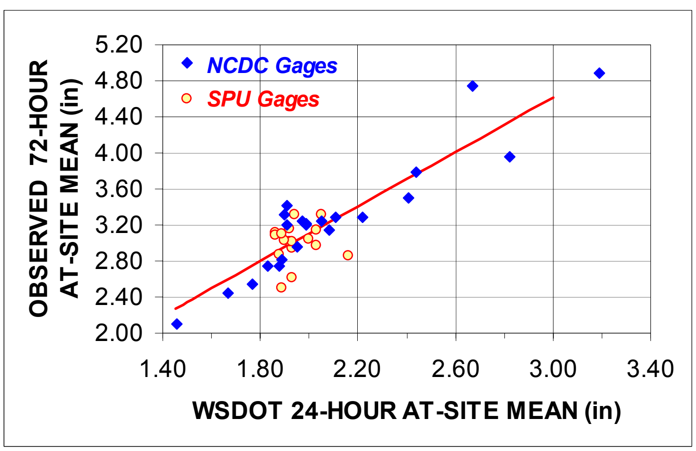


Figure 17b – Relationship Between Observed 72-Hour At-Site Mean Values and 24-Hour At-Site Mean Values from WSDOT[19] Gridded Dataset for Location of Precipitation Gages

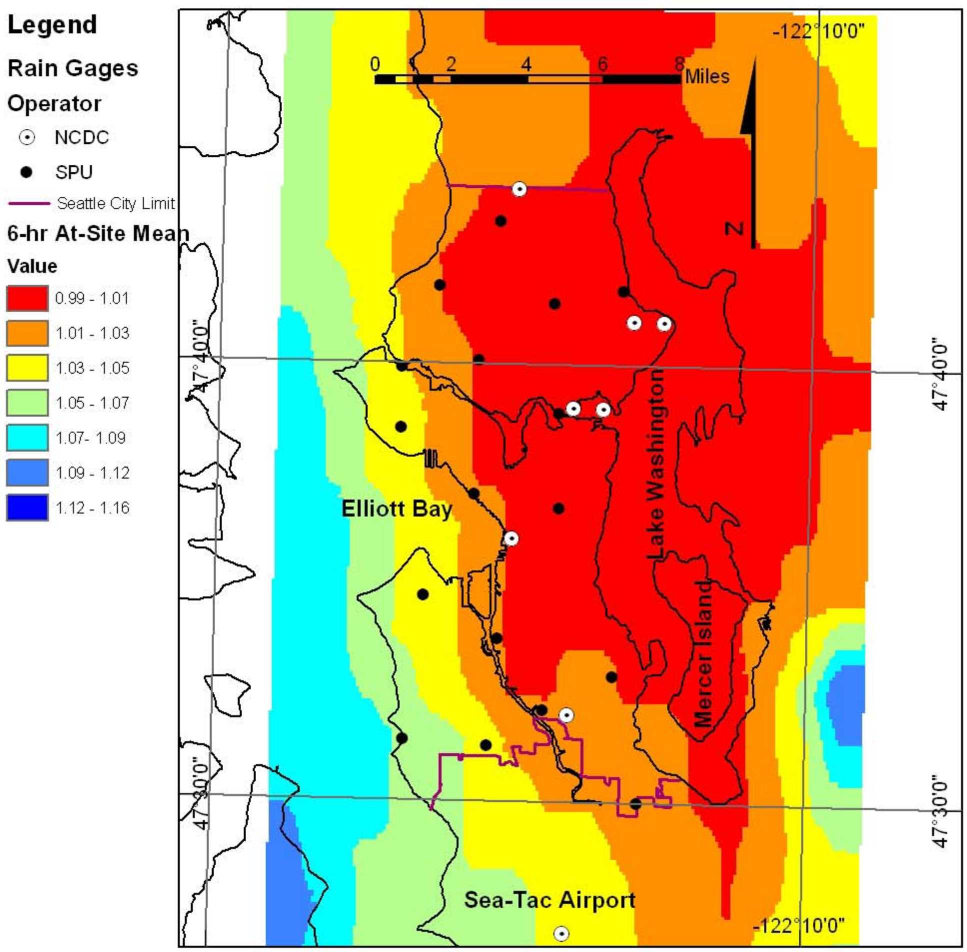


Figure 18a – Color-Shaded Contour Map of At-Site Mean Values for 6-Hour Precipitation

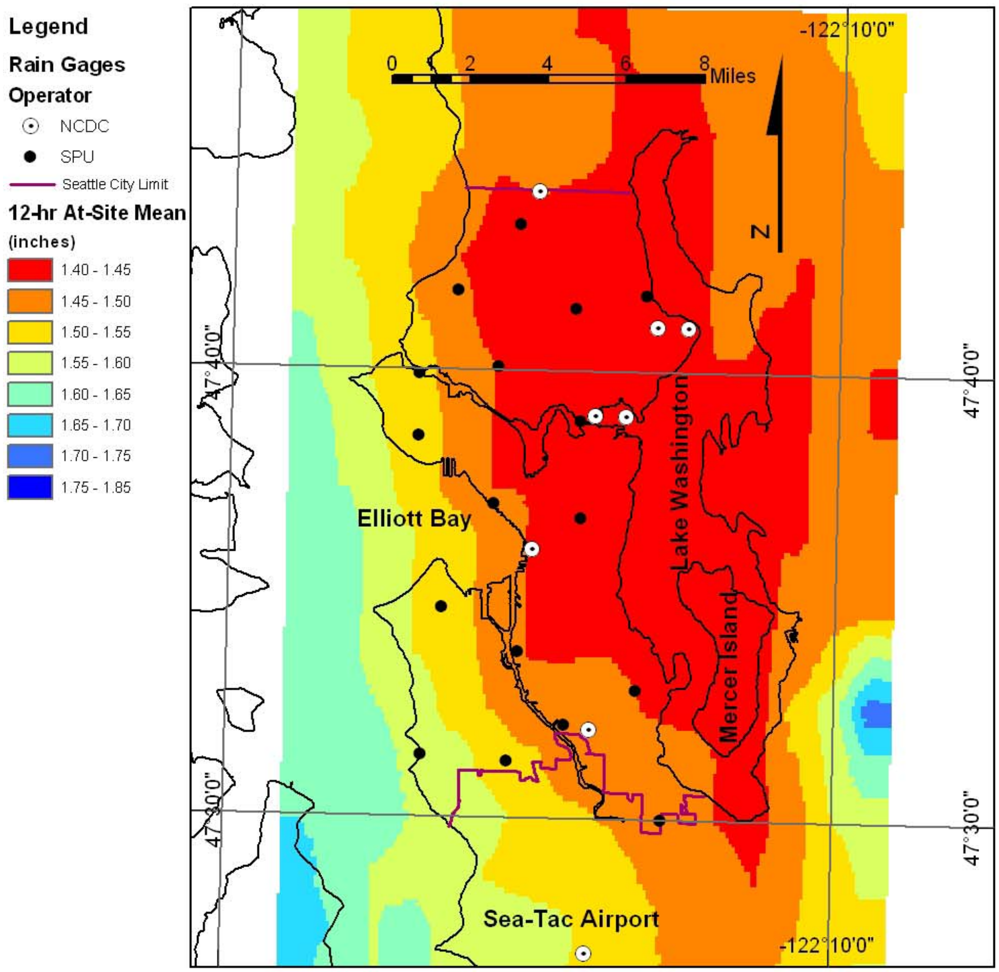


Figure 18b – Color-Shaded Contour Map of At-Site Mean Values for 12-Hour Precipitation

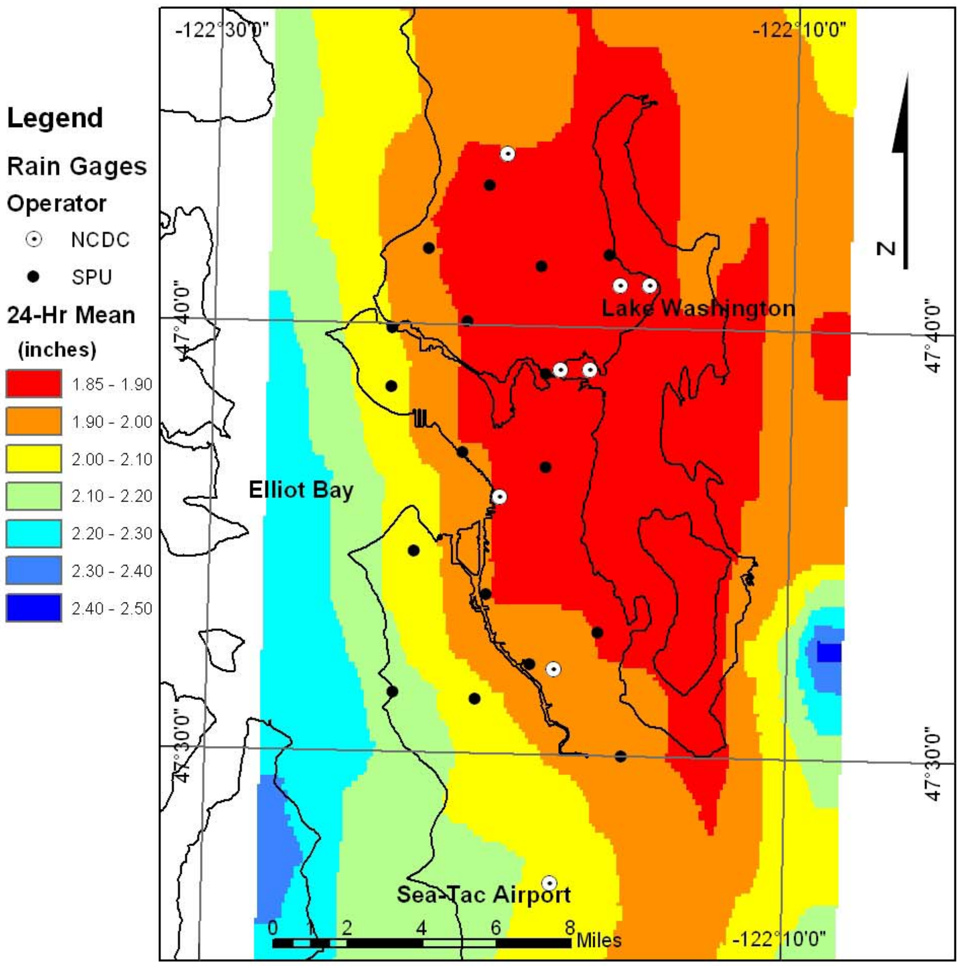


Figure 18c – Color-Shaded Contour Map of At-Site Mean Values for 24-Hour Precipitation

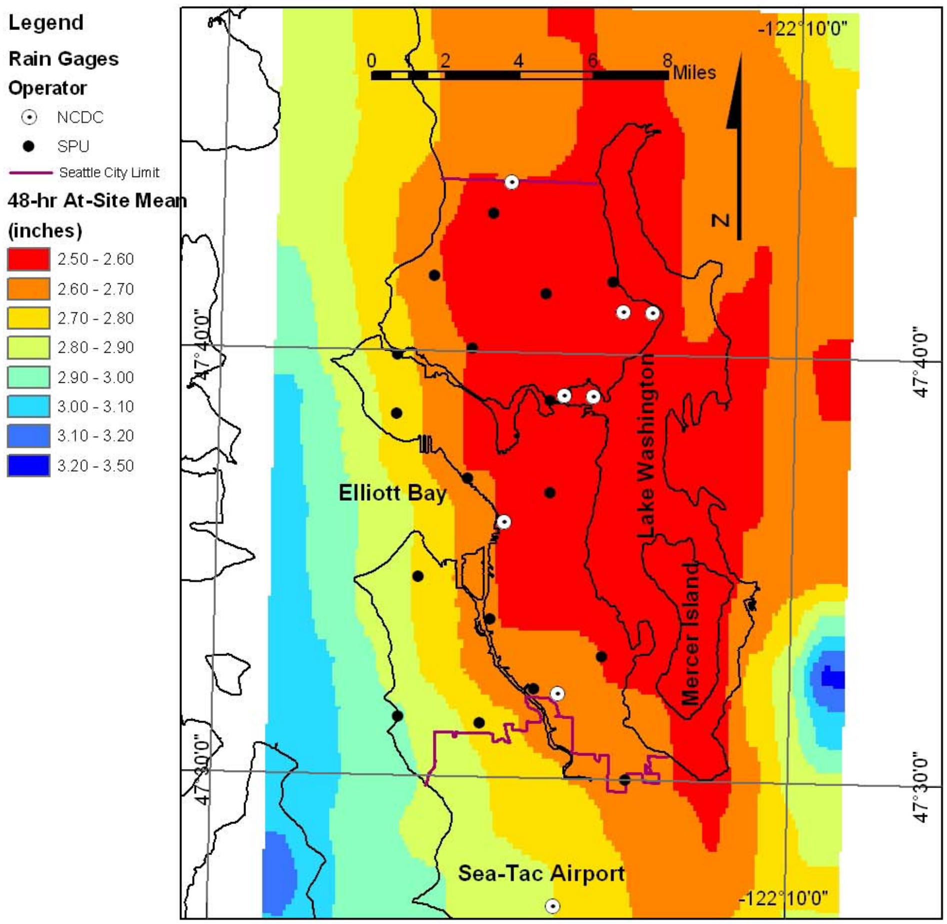


Figure 18d – Color-Shaded Contour Map of At-Site Mean Values for 48-Hour Precipitation

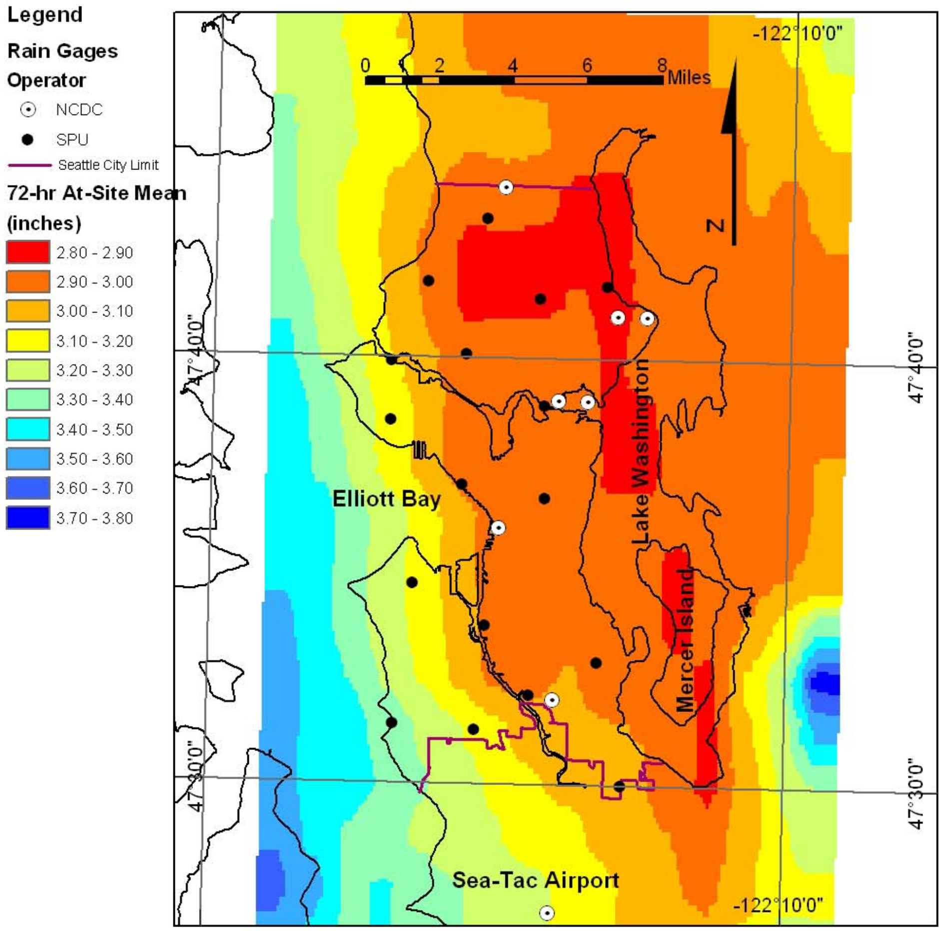


Figure 18e – Color-Shaded Contour Map of At-Site Mean Values for 72-Hour Precipitation

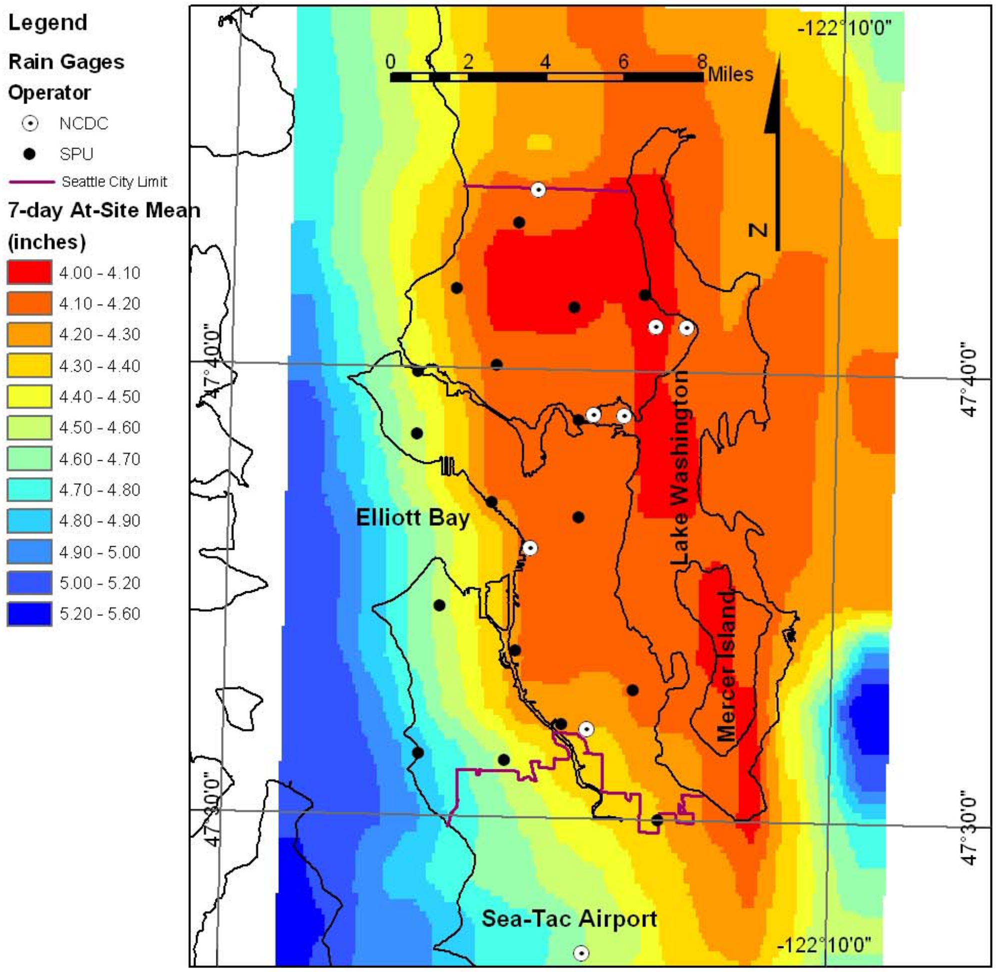


Figure 18f – Color-Shaded Contour Map of At-Site Mean Values for 7-Day Precipitation

STORM CHARACTERISTICS FOR DESIGN STORMS

Homogeneity as applied to design storms refers to the statistical similarity of pertinent storm characteristics, and to the geographical/climatological region wherein the storm characteristics would be considered similar. In this application, statistical similarity refers to the similarity of the means and variances of storm characteristics such as depth-duration relationships, and magnitude and sequencing of incremental precipitation amounts within the storm. Descriptions of the storm characteristics that were measured and used in the development of design storms are contained in a later section.

Design storms are constructed in a dimensionless format and are scaled for usage based on some indexing amount, such as the 24-hour, *n*-year precipitation. Use of a dimensionless shape-function for the design storm allows it to be applicable over a much larger geographical area than IDF curves. In particular, storm characteristics are sufficiently similar in the Puget Sound Lowlands, Lowlands in the Centralia to Vancouver Washington area, and the Willamette Valley that this geographic area has been determined in previous studies to be a homogeneous region for the purposes of developing design storms (Frederick et al[4], Miller[10], Schaefer[15,16,17,18,19]). The geographical area described above includes Climatic Zones 31 and 32 shown in Figure 3.

Given this past experience, storm characteristics were measured for large historical storms in the Seattle study area and compared to storm characteristics from a prior study of storms in Washington State (Schaefer[15]). These comparisons revealed that storm characteristics for the Seattle area are consistent with storm characteristics from the larger geographic area of Climatic Zone 31. Therefore, storm events from Climatic Zone 31 were used to augment the database of storms from the Seattle study area. This was done to increase the number of storms in the sample set and provide for a representative sample of storms.

Short-Duration, Intermediate-Duration, and Long-Duration Storms
Success in rainfall-runoff modeling using an event-based approach is dependent in-part upon utilizing a design storm that contains storm characteristics that are representative of the site of interest. In the Pacific Northwest, west of the Cascade Mountains, there are three distinctive categories of storm types. These storm types may be generally categorized as short-duration, intermediate-duration, and long-duration storms (Schaefer[15]).

Storms were categorized as being short, intermediate or long-duration based on the storm duration at which precipitation within the storm was most rare. Specifically, precipitation at the 2-hour, 6-hour, and 24-hour durations was measured for each storm event and the recurrence interval for precipitation was computed for each duration. The storm event was categorized as being short, intermediate or long-duration based on whether the precipitation measured at the 2-hour, 6-hour, or 24-hour duration respectively, was most rare.

Short-duration storms are primarily warm season events (Figure 23a). Periods of intense precipitation may last from 10-30 minutes with precipitation commonly occurring over a 1-hour to 6-hour period. These storms are limited in areal coverage but can produce very high intensities over isolated areas. These storms are often termed thunderstorms as they are sometimes accompanied by thunder, lightning, and hail. They can produce very flashy runoff hydrographs with a large flood peak, particularly in urban watersheds where much of the land surface is covered by imperious surfaces. The short-duration storm is often the controlling storm type for sizing conveyance structures in urbanized areas. Figures 19a,b depict examples of short-duration storms.

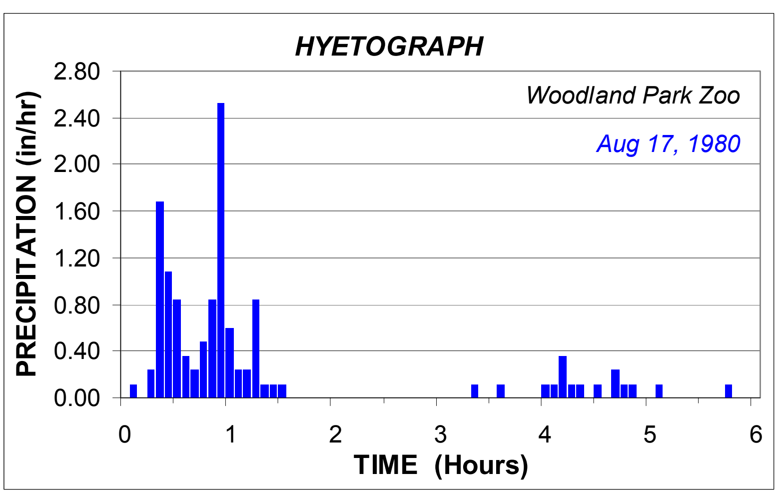


Figure 19a – Example of Short-Duration Storms Observed in Seattle Metropolitan Area

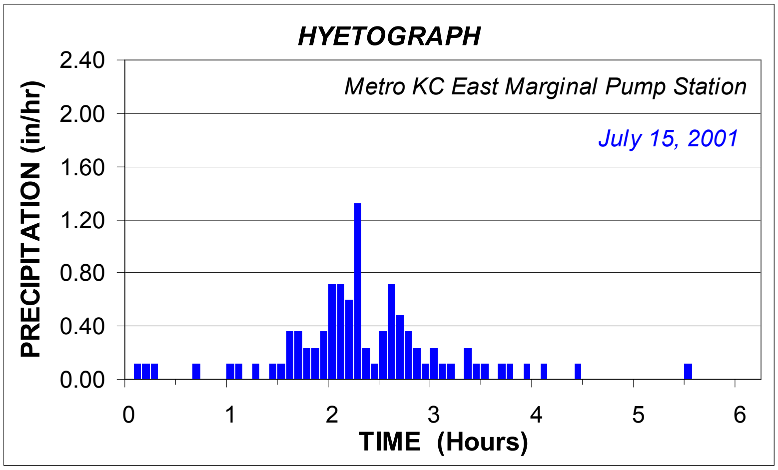
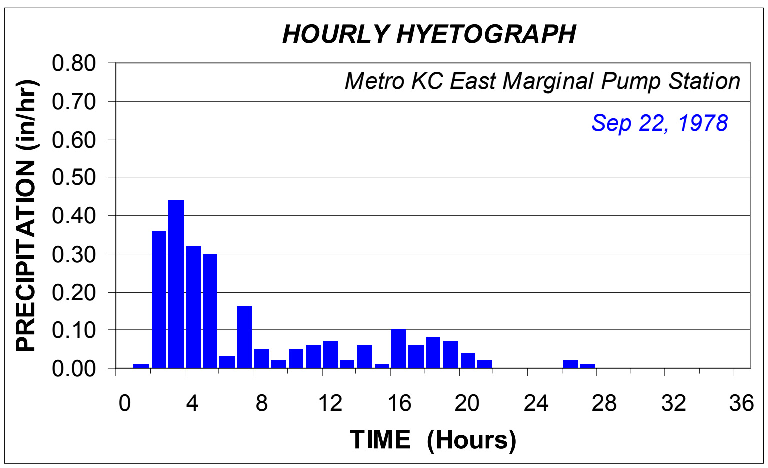
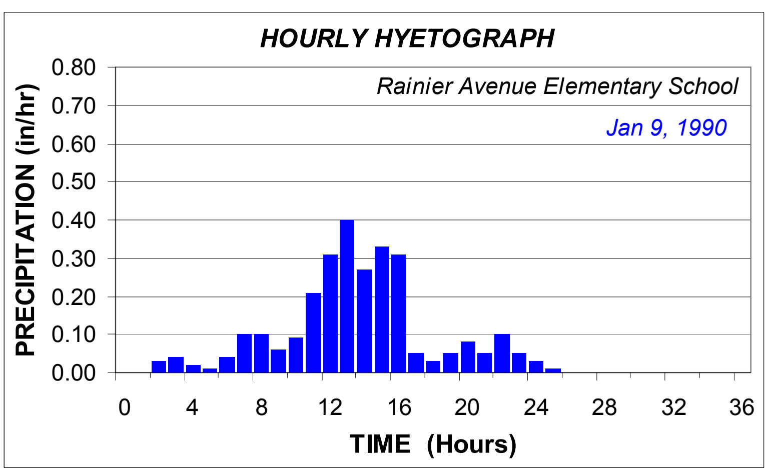


Figure 19b – Example of Short-Duration Storms Observed in Seattle Metropolitan Area

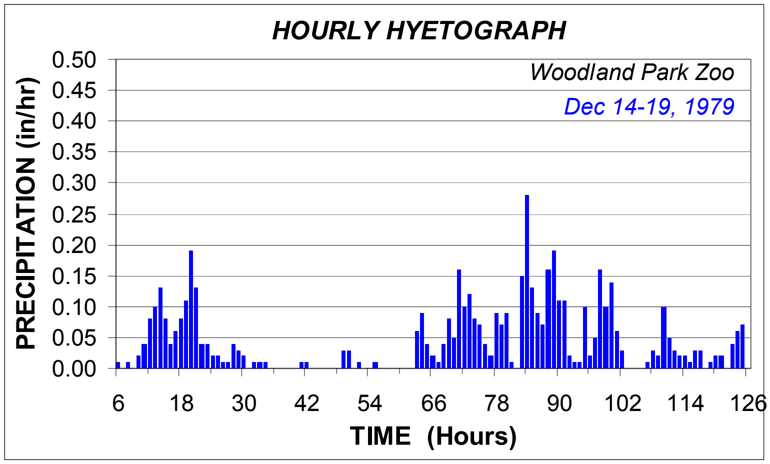
Intermediate-durations storms can occur throughout the year but are most common in the fall to early-winter seasons (Figure 23b). These storms often contain moderate to high intensities for a period of several hours, and precipitation commonly occurs over a 6-18 hour period. They can produce flood hydrographs that are flashy with a large peak discharge and a moderate runoff volume. Figures 20a,b depict examples of intermediate-duration storms.

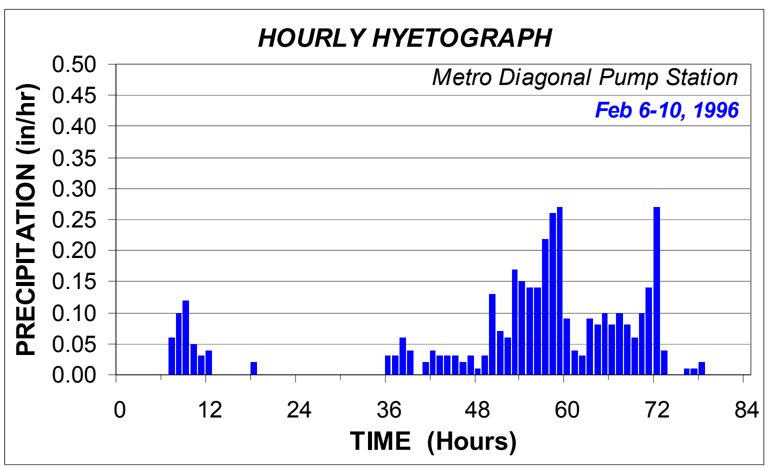




Figures 20a,b – Examples of Intermediate-Duration Storm Observed in Seattle Metropolitan Area

Long- duration storms are primarily late-fall and winter season events (Figure 20c). These storms are characterized by low to moderate intensities and have durations varying from near 24-hours to over 72-hours. These storms are commonly intermittent in nature containing multiple periods of precipitation over several days. The long duration storms are associated with synoptic scale (continental scale) weather systems originating over the Pacific Ocean and precipitation commonly extends over very large areas (Miller[10]). This type of storm typically produces floods with a sustained flood peak that is well supported by a large runoff volume. The long duration storm is usually the controlling storm type for design/analysis of stormwater detention facilities where runoff volume, in addition to flood peak discharge, is a primary consideration. Figures 21a,b depict examples of long-duration storms.





Figures 21a,b – Examples of Long-Duration Storm Observed in Seattle Metropolitan Area

Selection of Storms for Analysis

A catalog of storms was assembled for short, intermediate and long-duration storms for use in developing the sample set of storm characteristics for analysis. In general, there are two considerations in selecting storms for analysis. First, a large sample set of storms is desired to provide a representative sample for analysis. Second, the design storms will frequently be used for modeling rare storm events. Therefore, it is desirable to select rare storms for analysis to provide consistency between analysis and application. However, these criteria are competing in that it is not possible to restrict the selection to rare storms and yet produce a large sample set. If the threshold for storm selection is set too high, an insufficient number of storms will be available to provide a representative sample. Conversely, if the threshold is set too low, then common storms will be included that may not be representative of the more severe storm events. A balance between these two considerations was attained by utilizing a threshold of a 5-year recurrence interval for storm selection.

Design storms will also be used for depicting common storm events with recurrence intervals such as 2-years and 6-months. There is a logical question of how well design storms developed from rare storms will perform in depicting the storm characteristics for common storm events? Studies of storm characteristics by Frederick et al[4], found small differences between dimensionless storm characteristics for common and rare storm events in the Pacific Northwest. These differences become more prominent as the dimensionless design storms are scaled to larger (rarer) storm events. Conversely, these differences are less significant when smaller scaling is required for common events. Therefore, while the design storms provided here are intended primarily for application with more rare storm events, they will provide reasonable results in depicting the storm characteristics of common storms.

Assembly of the storm catalog (Appendix C) was accomplished by selection of noteworthy storms that had been observed at the 17 gage SPU gaging network. Storm selection proceeded as follows:

1. A recurrence interval was computed for each precipitation annual maximum for all SPU gages at the 2-hour, 6-hour and 24-hour durations using the findings of the regional precipitation-frequency analysis discussed earlier.
2. A separate list of candidate storms was prepared for short, intermediate, and long-duration storms for those storms (storm dates) whenever precipitation annual maxima exceeded the 5-year recurrence interval at either the 2-hour, 6-hour or 24-hour duration, respectively.
3. The three lists of candidate storm dates were reviewed and duplicate storm dates were identified. Whenever duplicate storm dates were identified, the storm (storm date) was retained on the list for the duration where the precipitation annual maximum was the most rare and removed from the lists for the other duration(s).
4. This process yielded a separate storm catalog for the short, intermediate, and long-duration storms for use in analysis of storm characteristics.

Measurement of Storm Characteristics

The approach taken in this study was to develop design storms that incorporate those storm characteristics that can have a significant effect on the magnitude of the peak discharge and stormwater runoff volume, and can affect the shape of the runoff hydrograph. This approach utilizes the procedures originally developed by Schaefer[15] in a study of extreme storms in Washington. Based on these considerations, storm characteristics of interest included:

- shape of the hyetograph (macro storm pattern)
- magnitude of incremental precipitation amounts within the storm
- elapsed time to occurrence of the high intensity portion of the storm
- sequencing of incremental precipitation amounts in the high intensity portion of storm
- sequencing of incremental amounts in the period of maximum 24-hour precipitation
- duration of continuous precipitation for the period of storm activity
- length of dry periods in intermittent storms

The measurement and method of analysis for each of these storm characteristics for the short, intermediate, and long-duration design storms is presented in the following sections.

Shape of the Hyetograph (Storm Macro Pattern)
The general shape of historical hyetographs was analyzed by categorization of the hyetographs into one of twelve generalized storm macro patterns[15] (Figure 22). As an initial measure of hyetograph shape, the frequency of occurrence of continuous versus intermittent patterns was also computed. As with any generalized categorization system, latitude and judgment are required in assigning historical hyetographs to one of the generalized patterns. This analysis provided a rough measure of the more frequently occurring storm macro patterns.

Magnitude of Incremental Precipitation Amounts within the Storm
The magnitudes of the incremental precipitation amounts within storms are important characteristics of hyetographs and design storms. In order to allow comparisons between storms, the magnitude of incremental precipitation amounts are expressed as dimensionless ratios of the precipitation amount for the duration used in indexing the storms. In particular, the magnitude of the maximum incremental amounts for the high-intensity portion of the storm is a critical factor in determining the magnitude of the runoff peak discharge in small urbanized watersheds.

Elapsed Time to Occurrence of the High Intensity Portion of the Storm
The elapsed time to the occurrence of the high-intensity portion of the storm affects both the magnitude of the runoff peak discharge and the shape of the runoff hydrograph. When the highest-intensities occur near the end of the storm (back-loaded storm), surface infiltration rates are likely to be lower due to wetting of the soil from prior precipitation. All other factors being equal, this generally results in higher runoff rates and larger peak discharges. With regard to stormwater detention facilities, a back-loaded storm results in the flood peak arriving after the detention pond is partially filled from prior runoff. This situation generally results in more stringent conditions for storage and passage of floodwaters. Thus, the elapsed time to the high-intensity portion of the storm can be an important factor in assembly of design storms.

Sequencing of Incremental Precipitation Amounts in the High Intensity Portion of Storm
The sequence order of the incremental precipitation amounts during the high intensity portion of the storm can affect the magnitude of the resultant runoff peak discharge. Herein, the sequence numbers 1, 2 and 3 refer to the largest, 2nd largest and 3rd largest incremental precipitation amounts during the high-intensity portion of the storm. Six sequences are possible: 123; 132; 213; 312; 231; and 321.

Several high intensity sequences were measured for each of the short, intermediate, and long-duration storms to assist in the construction of design storms. The duration of the high intensity segments and durations of the incremental precipitation increments are listed in Table 7a.

Table 7a – Inter-durations of High Intensity Storm Segments
for Short, Intermediate and Long-Duration Storms

STORM DURATION	DURATION (Hours)	
	INCREMENTAL PRECIPITATION	TOTAL DURATION STORM SEGMENT
SHORT	5-min	15-min
SHORT	15-min	45-min
SHORT	1-hour	3-hour
INTERMEDIATE	15-min	45-min
INTERMEDIATE	1-hour	3-hour
LONG	15-min	45-min
LONG	1-hour	3-hour
LONG	6-hour	24-hour

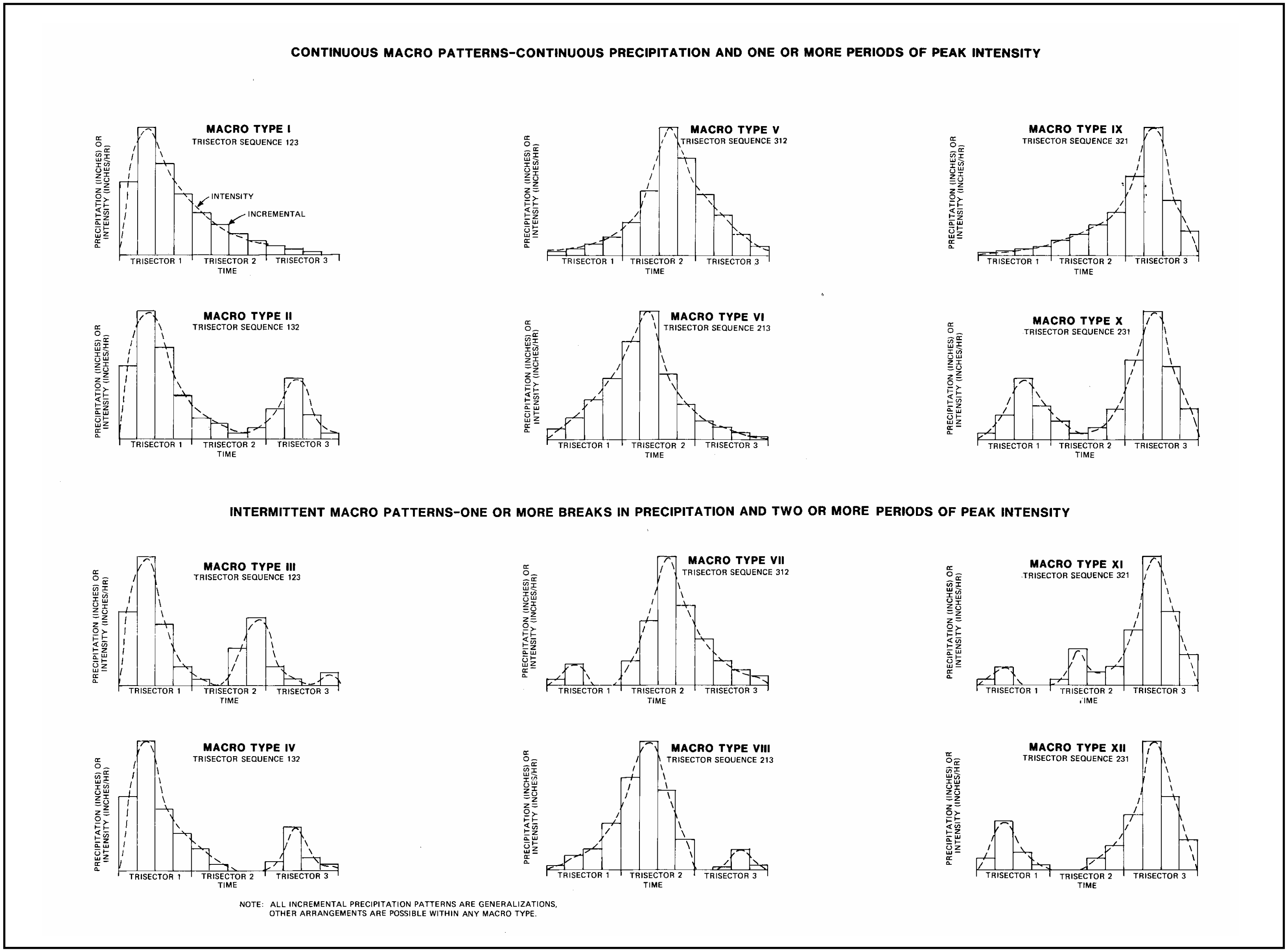


Figure 22 – Categorization of Hyetographs into Twelve General Macro Patterns (Schaefer[15])

Sequencing of Incremental Amounts in the Period of Maximum 24-Hour Precipitation for Long-Duration Storms

The sequence order of the incremental precipitation amounts during the greatest 24-hour period of precipitation also affects the magnitude of the resultant runoff peak discharge for long-duration storms. Here, the sequence numbers 1, 2, 3 and 4 refer to the largest, 2nd largest. 3rd largest and 4th largest 6-hour incremental precipitation amounts during the greatest 24-hour block of precipitation.

Given the four sequence numbers, there are 24 possible sequences. However, there were insufficient data to estimate the frequencies of all 24 combinations. Therefore, four basic sequences were examined that emphasized the location of the largest 6-hour increment of precipitation (i.e. 1xxx , x1xx , xx1x , xxx1). Sequence 1 has the largest 6-hour block occurring first and sequence two has the largest 6-hour block occurring from the 7th to the 12th hour in the 24-hour sequence, etc.

Duration of Continuous Precipitation for the Period of Storm Activity

Many storms are intermittent in nature and thus the length of the period of continuous precipitation varies between storms. This storm characteristic was measured by simply recording the period during which precipitation was continuous during the storm.

Length of Dry Period in Intermittent Storms

For storms that were intermittent, a measurement was made of the length of the dry period between continuous segments of precipitation. For intermittent storms with three or more continuous segments of precipitation, the length of the dry period was measured between the segment of continuous precipitation with the largest total precipitation amount and the adjacent segment with the next largest precipitation amount. Measurement of this storm characteristic was applicable to long-duration storms.

Total Storm Duration

The elapsed time from the start to end of precipitation was measured for long-duration storms. This measure is particularly useful for intermittent storms that have periods of continuous precipitation and dry intervening periods.

Seasonality of Storms

The term *seasonality of storms* is intended to describe the frequency of occurrence of storms that have exceeded the 5-year recurrence interval threshold at the various durations. Seasonality information is helpful in selection of realistic antecedent soil moisture conditions for conducting rainfall-runoff analyses for the short, intermediate and long-duration design storms. It may also be helpful for addressing issues that are seasonally dependent at specific projects.

Seasonality histograms are shown in Figures 23a,b,c for the short, intermediate and long-duration storms. A review of the histograms shows short duration storms to be primarily warm season events with storms occurring in the late-spring, summer, and early-fall of the year. Long-duration storms are primarily late-fall and winter events. Intermediate storms are transitional between the short and long-duration storms occurring primarily in early-fall through late-fall of the year.

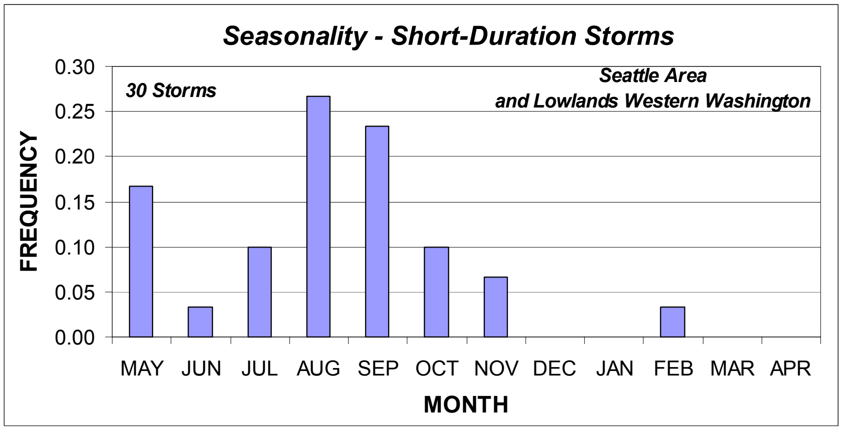


Figure 23a – Seasonality of Short-Duration Storms for the Seattle Metropolitan Area

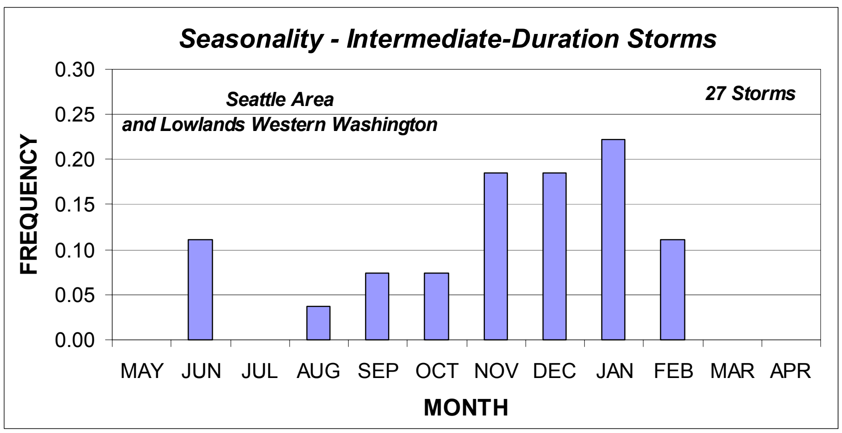


Figure 23b – Seasonality of Intermediate-Duration Storms for the Seattle Metropolitan Area

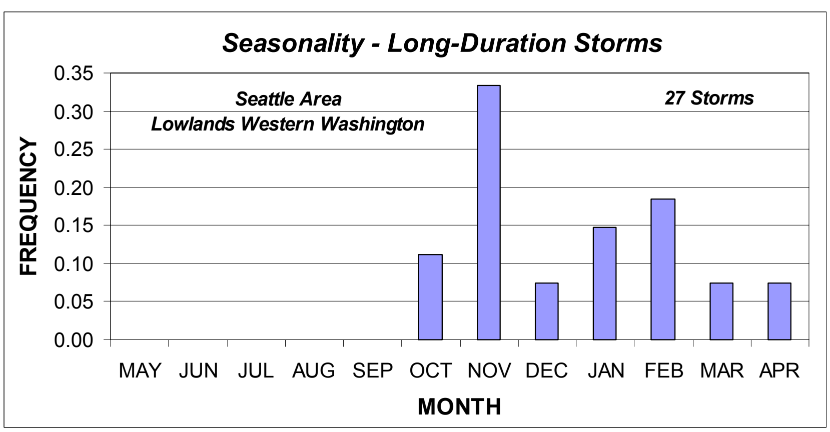


Figure 23c – Seasonality of Long-Duration Storms for the Seattle Metropolitan Area

ASSEMBLY OF DESIGN STORMS

The objective in constructing design storms was to provide storms that contained storm characteristics that were most representative of the conditions to be expected in the Seattle Metropolitan area. Therefore, mean or median values were used for those storm characteristics that could be described numerically. Values that occurred most frequently were used for those storm characteristics that were described by a categorization process, such as storm macro patterns and sequences of incremental precipitation amounts. Values of storm characteristics that were used for assembly of the short, intermediate and long-duration design storms are presented in the following sections.

A "24-hour design storm", with a total duration of 24-hours, is also needed for some stormwater applications where past policies have required use of a 24-hour storm. A 24-hour design storm has been developed using the maximum 24-hour precipitation in the long-duration design storm. The 24-hour design storm is described in Appendix D.

Scaling of Design Storms

As indicated previously, creation of design storms in a dimensionless format allows scaling of the design storms to any site-specific precipitation magnitude desired by the user. Specifically, the short, intermediate, and long-duration design storms have been rendered dimensionless by indexing the incremental precipitation amounts within the storms by the 2-hour, 6-hour, and 24-hour precipitation amounts, respectively. In application to a site-specific project, the *n*-year short, intermediate, or long-duration design storm can be developed by scaling (multiplying) the selected design storm by the *n*-year 2-hour, 6-hour, or 24-hour amount, respectively (Table 7).

Table 7 – Scaling of Dimensionless Design Storms

DESIGN STORM	DURATION OF PRECIPITATION USED FOR SCALING STORM	TOTALDURATION OF DESIGN STORM
Short	2-hour	3-hour
Intermediate	6-hour	18-hour
24-Hour (Appendix D)	24-hour	24-hour
Long	24-hour	64-hour

Assembly of Short-Duration Design Storms

Summary statistics for storm characteristics observed within short-duration storms are presented in Tables 8a,b,c,d,e,f. The storm characteristics used to assemble the short-duration design storm are listed in Table 9. Minor adjustments were made to the values of some storm characteristics for compatibility with the collection of storm characteristics. The dimensionless short-duration design storm is depicted in Figure 24 and dimensionless ordinate values are listed with a 5-minute time-step in Appendix D and in electronic files that accompany this report. The intensity index on the ordinate axis of Figure 24 is a dimensionless measure of precipitation intensity. Dimensionless ordinate values become precipitation intensities (in/hr) when scaled by the 2-hour precipitation amount for the selected recurrence interval for the project site of interest.

Table 8a – Frequency of Occurrence of Storm Macro Patterns for Short-Duration Storms

<table>
<tr><th colspan="12">MACRO STORM PATTERNS</th></tr>
<tr><th>I</th><th>II</th><th>III</th><th>IV</th><th>V</th><th>VI</th><th>VII</th><th>VIII</th><th>IX</th><th>X</th><th>XI</th><th>XII</th></tr>
<tr><td colspan="4">70%</td><td colspan="4">20%</td><td colspan="4">10%</td></tr>
</table>

Table 8b – Sample Statistics for Ratios of the Maximum 2-Hour Precipitation Amount for Inter-durations for Storms More Rare than the 5-Year Event at the 2-Hour Duration

	INTER-DURATIONS FOR SHORT-DURATION STORMS													
	5-mn	10-mn	15-mn	20-mn	30-mn	45-mn	60-mn	75-mn	90-mn	2-hr	3-hr	4-hr	5-hr	6-hr
Mean	0.189	0.299	0.410	0.457	0.582	0.705	0.815	0.875	0.931	1.000	1.055	1.096	1.125	1.152
Std Dev	0.083	0.115	0.147	0.165	0.168	0.155	0.127	0.104	0.075		0.068	0.117	0.156	0.192
Skew	1.09	0.86	0.71	0.82	0.80	0.31	-0.44	-0.97	-2.06		1.88	1.23	1.55	1.92

Table 8c – Frequencies of Various Sequences of Three Largest 5-Minute Precipitation Increments within the Largest 15-Minute Precipitation Increment

Sequence	123	132	213	312	231	321
Frequency	13%	13%	**27%**	20%	20%	7%

Table 8d – Frequencies of Various Sequences of Three Largest 15-Minute Precipitation Increments within the Largest 45-Minute Precipitation Increment

Sequence	123	132	213	312	231	321
Frequency	27%	13%	**40%**	0%	7%	13%

Table 8e – Frequencies of Various Sequences of Three Largest 1-Hour Precipitation Increments within the Largest 3-Hour Precipitation Increment

Sequence	123	132	213	312	231	321
Frequency	30%	3%	**37%**	30%	0%	0%

Table 8f – Summary Statistics of Selected Storm Characteristics

SUMMARY STATISTIC	ELAPSED TIME TO OCCURRENCE OF PEAK INTENSITY (Min)	DURATION OF CONTINUOUS PRECIPITATION (Min)
MEAN	98-min	134-min
MEDIAN	80-min	115-min
STD DEV	60-min	69-min

Table 9 – Temporal Storm Characteristics used in Assembly of Short-Duration Design Storm

STORM TEMPORAL CHARACTERISTICS	SELECTED VALUE
Storm Macro Pattern	I
Elapsed Time to Peak Intensity	80-min
Magnitude of Incremental Precipitation Amounts	Mean Values (Table 8b)
Duration of Continuous Precipitation	180-min
Sequence of 5-Minute Increments within Maximum 15-Minute Amount	213
Sequence of 15-Minute Increments within Maximum 45-Minute Amount	213
Sequencing of 1-Hour Increments within Maximum 3-Hour Amount	213

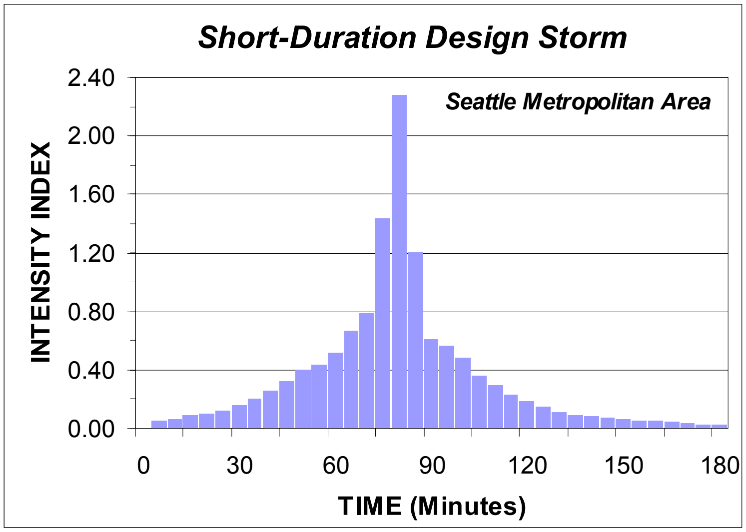


Figure 24 – Dimensionless Short-Duration Design Storm for Seattle Metropolitan Area

Assembly of Intermediate-Duration Design Storms

Summary statistics for storm characteristics observed within intermediate-duration storms are presented in Tables 10a,b,c,d,e. A review of the storm data and Table 10a revealed that about two-thirds of the intermediate-duration storms have continuous precipitation throughout the storm (macro patterns I,II,V,VI,IX,X). Therefore, the intermediate-duration design storm was constructed using a continuous precipitation pattern. The other storm characteristics used to assemble the intermediate-duration design storm are listed in Table 11. Minor adjustments were made to the values of some storm characteristics for compatibility with the collection of storm characteristics.

The dimensionless intermediate-duration design storm is depicted in Figure 25 and dimensionless ordinate values are listed with a 10-minute time-step in Appendix D and in electronic files that accompany this report. The intensity index on the ordinate axis of Figure 25 is a dimensionless measure of precipitation intensity. Dimensionless ordinate values become precipitation intensities (in/hr) when scaled by the 6-hour precipitation amount for the selected recurrence interval for the project site of interest.

Table 10a – Frequency of Occurrence of Storm Macro Patterns for Long-Duration Storms

MACRO STORM PATTERNS											
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
15%		10%		35%		20%		15%		5%	

Table 10b – Sample Statistics for Ratios of the Maximum 6-Hour Precipitation Amount for Inter-durations for Storms More Rare than the 5-Year Event at the 6-Hour Duration

	INTER-DURATIONS FOR INTERMEDIATE-DURATION STORMS													
	5-mn	10-mn	15-mn	30-mn	45-mn	60-mn	1-hr	2-hr	3-hr	6-hr	9-hr	12-hr	15-hr	18-hr
Mean	0.047	0.076	0.112	0.177	0.237	0.290	0.489	0.641	1.000	1.228	1.400	1.472	1.511	0.177
Std Dev	0.023	0.033	0.050	0.067	0.093	0.080	0.085	0.087		0.143	0.239	0.286	0.298	0.067
Skew	1.36	1.38	0.99	1.76	2.40	2.52	1.29	0.80		0.26	0.16	0.29	0.34	1.76

Table 10c – Frequencies of Various Sequences of Three Largest 15-Minute Precipitation Increments within the Largest 45-Minute Precipitation Increment for Intermediate-Duration Storms

Sequence	123	132	213	312	231	321
Frequency	25%	0%	38%	25%	13%	0%

Table 10d – Frequencies of Various Sequences of Three Largest 1-Hour Precipitation Increments within the Largest 3-Hour Precipitation Increment for Intermediate-Duration Storms

Sequence	123	132	213	312	231	321
Frequency	20%	0%	15%	**45%**	7%	13%

Table 10e – Summary Statistics of Selected Storm Characteristics for Intermediate-Duration Storms

SUMMARY STATISTIC	ELAPSED TIME TO OCCURRENCE OF PEAK INTENSITY (HR)	DURATION OF CONTINUOUS PRECIPITATION (HR)
MEAN	10-hr	14-hr
MEDIAN	10-hr	15-hr
STD DEV	4-hr	4-hr

Table 11 – Temporal Storm Characteristics used in Assembly of Intermediate-Duration Design Storm

STORM TEMPORAL CHARACTERISTICS	SELECTED VALUE
Storm Macro Pattern	V
Elapsed Time to Peak Intensity	10-hr
Magnitude of Incremental Precipitation Amounts	Mean Values (Table 10b)
Duration of Continuous Precipitation	18-hr
Sequence of 10-Minute Increments within Maximum 30-Minute Amount	213
Sequence of 20-Minute Increments within Maximum 60-Minute Amount	213
Sequencing of 1-Hour Increments within Maximum 3-Hour Amount	312

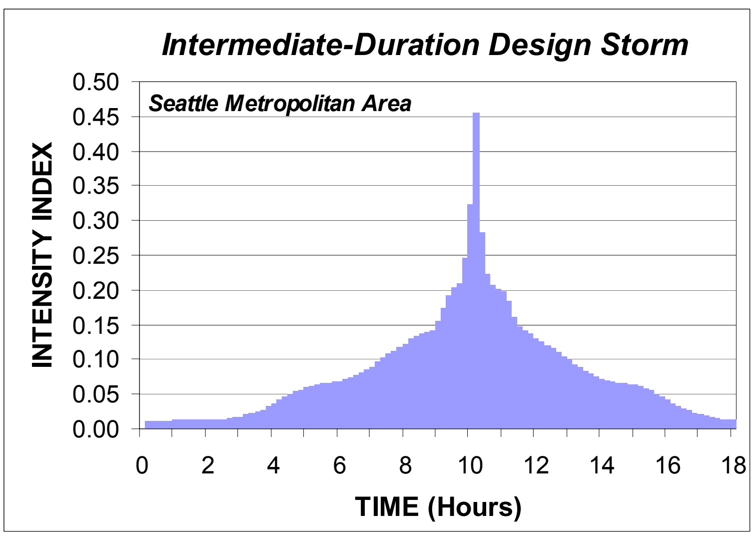


Figure 25 – Dimensionless Intermediate-Duration Design Storm for Seattle Metropolitan Area

Assembly of Long-Duration Design Storms

Summary statistics for storm characteristics observed within long-duration storms are presented in Tables 12a,b,c,d,e,f. A review of the storm data and Table 12a results shows that about two-thirds of the long-duration storms have intermittent patterns (macro patterns III,IV,VII,VIII,XI,XII). In addition, there is high diversity in the macro patterns in the sample set of 27 storms and no single macro pattern can be truly representative of the general shape of a long-duration storm. Therefore, two long-duration design storms have been constructed to reflect this diversity in storm patterns.

The first design storm (Figure 26a) is a front-loaded storm and has been assembled using the macro pattern observed most frequently. The second design storm (Figure 26b) is a back-loaded storm and has been constructed recognizing that the primary application of these storms will be in the design/analysis of stormwater detention facilities. This second design storm has a storm macro pattern that would likely provide a more stringent assessment of the performance of a stormwater detention facility. Accordingly, it is recommended as the design storm for design of stormwater detention facilities.

Both long-duration design storms have similar storm characteristics other than the macro patterns. The storm characteristics used to assemble the two long-duration design storms are listed in Tables 13a,b. Minor adjustments were made to the values of some storm characteristics for compatibility with the collection of storm characteristics. Dimensionless ordinates of the long-duration design storms are listed with a 10-minute time-step in Appendix D and in electronic files that accompany this report. The intensity index on the ordinate axes of Figures 26a,b are a dimensionless measure of precipitation intensity. Dimensionless ordinate values become precipitation intensities (in/hr) when scaled by the 24-hour precipitation amount for the selected recurrence interval for the project site of interest.

Table 12a – Frequency of Occurrence of Storm Macro Patterns for Long-Duration Storms

MACRO STORM PATTERNS											
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
25%		**32%**		0%		20%		3%		17%	

Table 12b – Sample Statistics for Ratios of the Maximum 24-Hour Precipitation Amount for Inter-durations for Storms More Rare than the 5-Year Event at the 24-Hour Duration

	INTER-DURATIONS FOR LONG-DURATION STORMS								
	5-mn	10-mn	15-mn	30-mn	1-hr	2-hr	3-hr	6-hr	9-hr
Mean	0.029	0.042	0.051	0.067	0.102	0.171	0.231	0.373	0.509
Std Dev	0.016	0.018	0.026	0.022	0.018	0.024	0.028	0.041	0.065
Skew	2.77	1.90	2.80	1.96	0.82	0.22	-0.28	0.08	-0.37

	INTER-DURATIONS FOR LONG-DURATION STORMS						
	12-hr	18-hr	24-hr	36-hr	48-hr	60-hr	72-hr
Mean	0.633	0.827	1.000	1.105	1.157	1.213	1.269
Std Dev	0.083	0.072		0.089	0.128	0.152	0.172
Skew	-0.83	-0.84		1.72	1.41	1.14	0.97

Table 12c – Frequencies of Various Sequences of Three Largest 15-Minute Precipitation Increments within the Largest 45-Minute Precipitation Increment for Long-Duration Storms

Sequence	123	132	213	312	231	321
Frequency	15%	8%	23%	**46%**	0%	8%

Table 12d – Frequencies of Various Sequences of Three Largest 1-Hour Precipitation Increments within the Largest 3-Hour Precipitation Increment for Long-Duration Storms

Sequence	123	132	213	312	231	321
Frequency	11%	7%	**33%**	**30%**	4%	14%

Table 12e – Frequencies for Location of Largest 6-Hour Precipitation Increments within the Largest 24-Hour Precipitation Increment for Long-Duration Storms

Sequence	1XXX	X1XX	XX1X	XXX1
Frequency	7%	**39%**	32%	21%

Table 12f – Summary Statistics for Selected Storm Characteristics for Long-Duration Storms

SUMMARY STATISTIC	ELAPSED TIME TO OCCURRENCE OF PEAK INTENSITY	DURATION OF CONTINUOUS PRECIPITATION	LENGTH OF DRY PERIOD IN INTERMITTENT STORMS	TOTAL STORM DURATION
MEAN	28-hours	34-hours	13-hours	62-hours
MEDIAN	23-hours	31-hours	11-hours	66-hours
STD DEV	16-hours	9-hours	10-hours	12-hours

Table 13a – Temporal Storm Characteristics used in Assembly of Front-Loaded Long-Duration Design Storm

STORM TEMPORAL CHARACTERISTICS	SELECTED VALUE
Storm Macro Pattern	IV
Elapsed Time to Peak Intensity	18-hr
Magnitude of Incremental Precipitation Amounts	Mean Values (Table 12b)
Duration of Continuous Precipitation	34-hr
Sequence of 10-Minute Increments within Maximum 30-Minute Amount	312
Sequence of 20-Minute Increments within Maximum 60-Minute Amount	312
Sequencing of 1-Hour Increments within Maximum 3-Hour Amount	213
Sequencing of 6-Hour Increments within Maximum 24-Hour Amount	3124
Length of Dry Period between Periods of Continuous Precipitation	13-hr
Total Storm Duration	64-hr

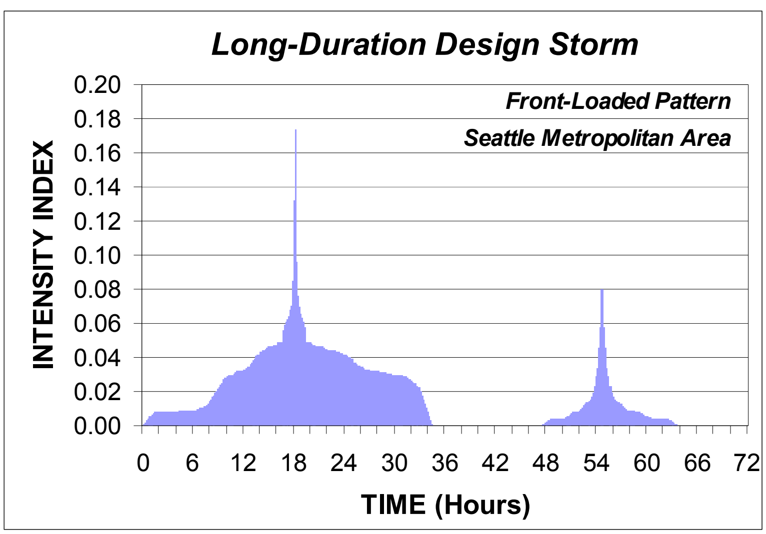


Figure 26a – Dimensionless Front-Loaded Long-Duration Design Storm for Seattle Metropolitan Area

Table 13b – Temporal Storm Characteristics
used in Assembly of Back-Loaded Long-Duration Design Storm

STORM TEMPORAL CHARACTERISTICS	SELECTED VALUE
Storm Macro Pattern	XII
Elapsed Time to Peak Intensity	47-hr
Magnitude of Incremental Precipitation Amounts	Mean Values (Table 12b)
Duration of Continuous Precipitation	34-hr
Sequence of 10-Minute Increments within Maximum 30-Minute Amount	312
Sequence of 20-Minute Increments within Maximum 60-Minute Amount	312
Sequencing of 1-Hour Increments within Maximum 3-Hour Amount	213
Sequencing of 6-Hour Increments within Maximum 24-Hour Amount	3124
Length of Dry Period between Periods of Continuous Precipitation	13-hr
Total Storm Duration	64-hr

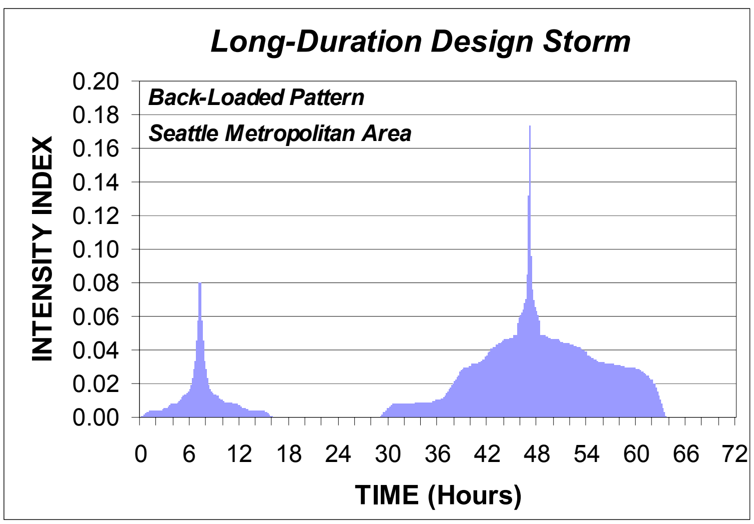


Figure 26b – Dimensionless Back-Loaded Long-Duration Design Storm
for Seattle Metropolitan Area

TRANSPOSING OF PRECIPITATION DATA FOR FILL-IN OF MISSING RECORDS

Homogeneity for transposing precipitation data from one site to another site is used in reference to the expected similarity of the time-series records at the two sites. In this application, the objective is to fill-in missing record at a *target gage* by transposing the data from a *source gage*. The transposition may be direct, or the original data from the source gage may be scaled based on some relationship between historical data at the two gages.

The similarity of time-series records, and thus, the suitability of transposition is typically interpreted/determined in terms of the nearness of the two sites for the storm duration of interest. Fill-in of missing record is best suited for precipitation data from long-duration general storms. These storm types typically contain low to moderate intensities and produce precipitation over large areas. The temporal patterns in these storms can likewise be expected to be similar over large areas.

Fill-in of missing records is difficult when precipitation is produced by convective storm cells that may be isolated or embedded within storms that produce more widespread precipitation. Precipitation from convective cells is generally short-lived and precipitation intensities and temporal patterns from convective cells can vary rapidly over relatively short distances. This combination of conditions makes it difficult to reliably estimate the magnitude and temporal pattern of precipitation at neighboring sites.

In addition to the considerations above, the suitability of transposition is also dependent upon the intended application of the precipitation time-series and whether the fill-in is for common storm events or larger/rare storm events. Since precipitation time-series can be used for a wide variety of purposes, transposition and fill-in of missing data may be appropriate for some applications and may not be appropriate for other applications.

Typical applications of precipitation time-series include:

- Data sources for investigation of citizen complaints of stormwater flooding problems
- Calibration of continuous hydrological models, such as HSPF[19], for watershed modeling (model calibration of observed streamflow using precipitation that generated the streamflow)
- Data sources for statistical analyses
- Input to continuous hydrological models for design of stormwater facilities (time-series may be observed, synthetic, or combination thereof)
- Input to continuous hydrological models for developing flood-frequency relationships as part of regional watershed planning (time-series may be observed, synthetic or combination)

Each of these applications will be discussed in a later section.

Correlation Analyses of Concurrent Precipitation

Similarity of precipitation at gages within a network can be analyzed in a number of ways. Correlation analysis is probably the most commonly used method for examining that relationship. Figures 27a,b depict scatterplots for correlation analyses of concurrent precipitation at Gages 03 and 11 for the 15-minute and 24-hour durations, respectively. Gages 03 and 11 are located 3 miles apart and have a southwest-northeast alignment, which is the predominant direction of movement for long-duration winter storms (Miller[10]). The datasets for correlation were assembled by utilizing the annual maxima at Gage 03 (explanatory variable) and then determining the maximum concurrent precipitation from Gage 11 for the storm date/time for the duration under investigation (response variable) for the period from 1978-2003.

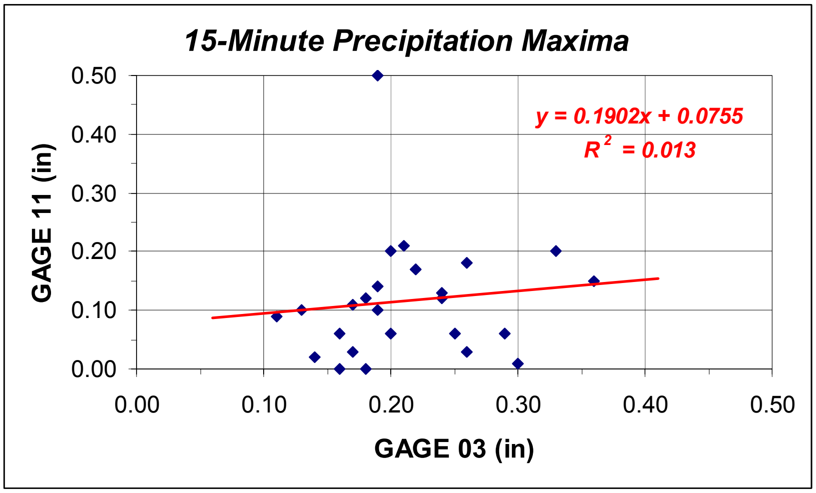


Figure 27a – Relationship Between Precipitation Annual Maxima at Gage 03 with Concurrent Precipitation at Gage 11 for 15-Minute Duration

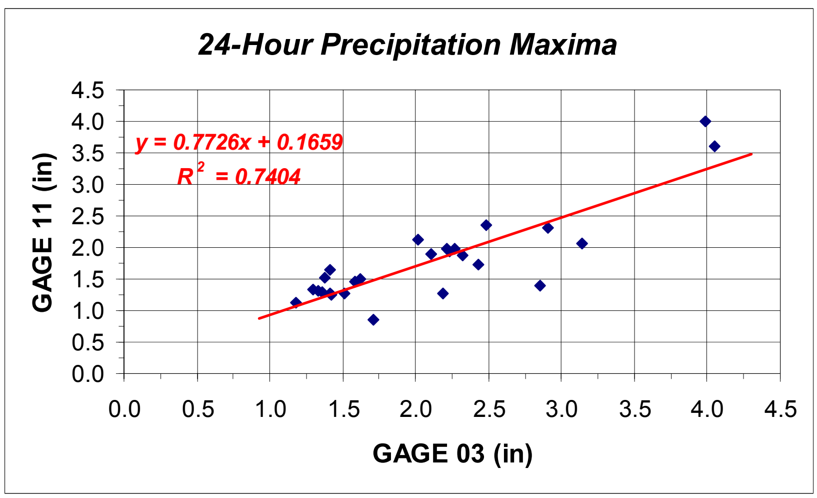


Figure 27b – Relationship Between Precipitation Annual Maxima at Gage 03 with Concurrent Precipitation at Gage 11 for 24-Hour Duration

A review of Figures 27a,b indicates concurrent precipitation data for 15-minute maxima are essentially independent. Thus, short-duration precipitation at a gage is generally a poor predictor of precipitation for neighboring gages. In contrast, 24-hour precipitation maxima are highly correlated. For this case, 24-hour precipitation at a gage is generally a good estimator of precipitation at neighboring gages. Analyses for the full suite of durations would show little or no correlation for durations from 5-minute through 60-minutes and increasing levels of correlation in progressing from 2-hour through 7-day durations. This behavior of correlation coefficients is consistent with the description provided in the earlier section regarding the limited areal coverage of convective cells as compared to the widespread areal coverage of long-duration storms.

Equivalent Independent Record Length (EIRL) Analyses
Computation of the Equivalent Independent Record Length (EIRL)[16,17] for the network is an alternative approach for measuring the similarity of precipitation between neighboring gages and in measuring performance of a network. EIRL is an accounting method that counts the number of separate storm dates as a measure of the independence of the annual maxima. This approach implicitly reflects the relationship between the network density and the areal coverage of the storms associated with the greatest precipitation magnitudes. In particular, it measures how frequently annual maxima at neighboring gages are produced by the same storm. Table 14 lists the findings of the EIRL analysis for the City of Seattle network of 17 precipitation gages.

A review of Table 14 shows that the majority of short-duration annual maxima are nearly independent of each other with regard to storm date/event. Conversely, the majority of longer-duration annual maxima have common storm dates/events. In simple terms, if a long-duration storm (24-hours and greater) of significant magnitude produces an annual maxima at one gage, that storm is likely to produce the annual maxima at many other surrounding gages. This reflects the widespread areal coverage associated with long-duration storms. In contrast, if a storm produces a significant precipitation amount at the 5-min to 15-min duration at one gage, that storm likely does not produce the 5-min to 15-min annual maxima at neighboring gages. This behavior reflects the limited areal coverage of short-duration high-intensity bursts of precipitation commonly associated with convective activity.

Table 14 – Results of Equivalent Independent Record Length Analysis
for City of Seattle Network of 17 Precipitation Gages

DURATION	STATION-YEARS OF RECORD	EIRL (Years)	EQUIVALENT NUMBER OF INDEPENDENT GAGES
5-MIN	607	400	11.2
10-MIN	611	415	11.5
15-MIN	609	400	11.2
20-MIN	616	400	11.0
30-MIN	615	385	10.6
45-MIN	614	350	9.7
60-MIN	604	315	8.9
2-HR	600	220	6.2
3-HR	612	165	4.6
6-HR	602	150	4.2
12-HR	602	150	4.2
24-HR	610	135	3.8
48-HR	419	70	2.8
72-HR	427	75	3.0
7-DAY	425	65	2.6

With regard to transposition of storms, the EIRL analysis indicates that transposition is least useful for the very short-duration high-intensity annual maxima. However, transposition would be expected to be suitable for describing the incremental precipitation amounts and temporal pattern for long-duration storms. These findings are consistent with the results of the correlation analyses described previously.

The findings of the correlation and EIRL analyses may also be used as part of quality checking of data to corroborate suspect data that may have been recorded due to some mechanical or electronic problem in the measurement and data logging process.

RECOMMENDATIONS FOR TRANSPOSITION AND FILL-IN OF MISSING RECORDS

In developing recommendations for transposition and fill-in of missing records, the five applications listed previously can be grouped into two general categories. The first category is for applications that require a predicted precipitation value that is as near to the actual precipitation (that would have been observed had the gage performed properly) as is possible to achieve. This situation applies to use with citizen complaints of flooding and for calibration of continuous hydrological models where there will be a direct comparison between cause and effect for a noteworthy storm/runoff event.

The second category is for applications where the accuracy of a specific fill-in value is not as stringent as that described above. In this latter case, the precipitation time-series are used for analyses that require that the overall statistical characteristics of the time-series are representative rather than a fill-in value be an accurate estimate of what actually occurred. If a significant amount of fill-in is required or if the fill-in period includes a noteworthy storm(s), then it is advisable to construct probability-plots for the annual maxima for the affected durations to confirm the fill-in values are consistent with the general behavior of the annual maxima data series.

Recommendations are made in Table 15 regarding transposition and fill-in of missing records based on consideration of the issues discussed in the prior sections. Terms used in Table 15 are described below.

Table 15 – Recommendations for Use of Transposition and Fill-In of Missing Data for Precipitation Time-Series for Various Applications

APPLICATIONS	SMALL STORM EVENTS THAT COMMONLY OCCUR	LARGER STORM EVENTS THAT PRODUCE ANNUAL MAXIMA	
	ALL DURATIONS	5-MIN to 60-MIN DURATIONS	2-HR to 7-DAY DURATIONS
Data Sources for Investigating Flooding Complaints	Not Applicable flooding complaints not associated with common events	Not Reliable unless corroborated by multiple gages	Reasonable Approach corroborate by multiple gages
Calibration of Hydrological Models	Reasonable Approach	Not Reliable unless corroborated by multiple gages	Reasonable Approach corroborate by multiple gages
Data Sources for Statistical Analyses	Reasonable Approach	Not Reliable unless corroborated by multiple gages	Reasonable Approach
Input to Hydrological Models for Stormwater Facility Design	Reasonable Approach	Feasible Approach suggest confirmation by probability-plot	Reasonable Approach suggest confirmation by probability-plot
Input to Hydrological Models for Regional Planning	Reasonable Approach	Feasible Approach suggest confirmation by probability-plot	Reasonable Approach suggest confirmation by probability-plot

Not Applicable – The phrase *Not Applicable* in Table 15 refers to the likelihood of experiencing flooding problems from very common storm events. It is expected that flooding problems would be associated with larger storm events. Thus, fill-in of common storm events would not likely affect the usage of storm data for investigation of flooding problems.

Not Reliable – The recommendation of transposition being *Not Reliable* is based on the findings of the EIRL analysis that shows that annual maxima at the shortest durations do not typically occur on the same storm date at neighboring stations. This reflects the very small areal coverage of the high-intensity bursts of precipitation. It also reflects the experience gained in comparing observed precipitation measurements at adjoining stations in the 17 gage network for short-duration precipitation maxima.

Corroboration by Multiple Gages – The recommendations in Table 15 includes a criterion that multiple gages be used to corroborate a temporal pattern as a condition for transposition. This criterion was specified because if several gages near a gage with missing record have similar temporal patterns and incremental precipitation magnitudes, it is reasonable to assume that the areal coverage of the storm period of interest was sufficiently widespread that the same temporal pattern would have affected the gage with the missing record. These conditions were rarely seen to occur for the short 5-min to 15-minute precipitation annual maxima data for the Seattle network. Corroboration is usually accomplished using a "nearest neighbor" approach. Estimation of precipitation for transposition can be accomplished using a spatial interpolation procedure such as the inverse distance-squared method (Smith[21]).

Use of Probability-Plots – Probability-plots are useful for comparing the magnitude of transposed precipitation with the magnitudes of precipitation that were observed within the precipitation time-series. Figures 8a through 12d are examples of probability-plots that show the frequencies (return periods) of annual maxima.

The basic idea is to avoid adding a large storm event as part of a transposition and fill-in of missing data that would distort the magnitude-frequency relationship for a given duration. This could occur, for example, if several intense 5-minute or 10-minute bursts were transposed from surrounding gages to fill-in various periods of missing record. This situation could result in distortion of the precipitation-frequency characteristics at the receiving (target) gage.

Heterogeneity of At-Site Means and Transposition of Long-Duration Precipitation

There appears to be a conflict between the finding that at-site means values for longer duration precipitation (24-hours and greater) vary across the Seattle Metropolitan area and the recommendation that transposition of missing data is best suited to long duration storm events. Although these two findings appear to be in conflict, they are both valid. There is a scale issue involved which relates to the size of the region and the distance between stations of interest. It is true that the at-site mean values vary from north to south across the Seattle Metropolitan area for the longer durations. Thus, it would be unreasonable to transpose data from the station furthest north to the station that is furthest south. While this trend across the region exists, it is also true that the differences between stations located at short distances from each other are sufficiently small, that it quite reasonable to transpose data between these neighboring stations.

SUMMARY

Precipitation annual maxima data series were assembled and analyzed for durations of 5-min; 10-min; 15-min; 20-min; 30-min; 45-min; 60-min; 2-hr; 3-hr; 6-hr; 12-hr; 24-hr; 48-hr; 72-hr; and 7-days for data collected from the SPU 17 gage network and gages in the national NOAA gaging network. The findings from those analyses can be summarized as follows.

1. Regional precipitation-frequency analyses were conducted for the 15 durations from 5-minutes through 7-days. The three-parameter Generalized Extreme Value (GEV) distribution was found to be the best choice for describing the precipitation magnitude-frequency characteristics in the Seattle Metropolitan Area. This is the same probability distribution found to be applicable to homogeneous climatic regions in large-scale regional studies conducted for both Washington and Southern British Columbia.
2. Regional values of the L-moment ratios L-Cv and L-skewness were determined for each of the 15 durations from 5-minutes through 7-days. These regional-average values were used to determine the distribution parameters for the GEV distribution for each of the 15 durations. This information can be used for computing precipitation magnitude-frequency estimates for any site in the Seattle Metropolitan Area for any of the 15 durations
3. The Seattle Metropolitan Area is homogeneous with regard to the magnitude-frequency characteristics of short-duration precipitation with durations of 3-hours or less. One set of Intensity-Duration-Frequency curves were developed for durations from 5-minutes through 180-minutes that are applicable to the entire Seattle Metropolitan Area.
4. The Seattle Metropolitan Area is heterogeneous with regard to the magnitude-frequency characteristics of longer-duration precipitation. Isopluvial maps are needed to describe the spatial variation of precipitation for durations of 6-hours and longer. Gridded datasets of at-site mean values were prepared for the Seattle Metropolitan Area to describe the spatial variability for durations of 6-hr, 12-hr, 24-hr, 48-hr, 72-hr and 7-days. These gridded datasets can be used to develop isopluvial maps for any recurrence intervals of interest.
5. Storm characteristics were measured for precipitation events that exceeded a 5-year recurrence interval at SPU gages. Statistical analyses were conducted for the storm characteristics and dimensionless design storms were developed for short, intermediate, and long-duration storm events. The short, intermediate, and long-duration design storms can be scaled to any site-specific recurrence interval using precipitation magnitudes at the 2-hour, 6-hour and 24-hour durations, respectively.
6. Transposition of periods of time-series data from a *source gage* to a *target gage* for fill-in of missing record is generally reasonable for precipitation produced by long-duration storms (24-hours and longer) when the inter-gage distance is several miles or less.
7. Transposition of time-series data is generally inappropriate for precipitation produced by short-duration storms and periods during storms with bursts of high-intensity precipitation. Transposition of time-series data is not recommended in these situations unless several gages can corroborate that the temporal pattern of the high-intensity precipitation had more widespread areal coverage and likely included the gage with the missing record.

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APPENDIX - A

L-MOMENT STATISTICS

L-MOMENT STATISTICS

L-moments are a dramatic improvement over conventional statistics for characterizing the variance and skewness of data, for describing the shape of a probability distribution, and for estimating the distribution parameters (Hosking[5], Hosking and Wallis[6]). They are particularly useful for describing environmental data that are often highly skewed. The at-site L-moment measure of location, and L-moment ratio measures of scale, skewness and kurtosis are:

Location, mean:

$$\text{Mean} = L_1 \quad \text{(A1)}$$

Scale, L-Cv (t_2):

$$t_2 = L_2/L_1 \quad \text{(A2)}$$

L-Skewness (t_3):

$$t_3 = L_3/L_2 \quad \text{(A3)}$$

L-Kurtosis (t_4):

$$t_4 = L_4/L_2 \quad \text{(A4)}$$

where:

$$L_1 = \beta_0 \quad \text{(A5)}$$

$$L_2 = 2\beta_1 - \beta_0 \quad \text{(A6)}$$

$$L_3 = 6\beta_2 - 6\beta_1 + \beta_0 \quad \text{(A7)}$$

$$L_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0 \quad \text{(A8)}$$

and where the at-site data are first ranked in ascending order from 1 to n ($x_{1:n}$) and:

$$\beta_0 = n^{-1} \sum_{j=1}^{n} x_j \quad \text{(A9)}$$

$$\beta_1 = n^{-1} \sum_{j=2}^{n} x_j\, [(j-1)/(n-1)] \quad \text{(A10)}$$

$$\beta_2 = n^{-1} \sum_{j=3}^{n} x_j\, [(j-1)(j-2)]/[(n-1)(n-2)] \quad \text{(A11)}$$

$$\beta_3 = n^{-1} \sum_{j=4}^{n} x_j\, [(j-1)(j-2)(j-3)]/[(n-1)(n-2)(n-3)] \quad \text{(A12)}$$

Regional L-moments ratios are obtained as weighted averages of the at-site L-moments ratios where the at-site values are weighted by record length. Specifically: n_i is the record length at site i of N sites: n_R is the total record length for the N sites in the region; t_2^i, t_3^i, t_4^i are L-moment ratios at site i ; and:

$$n_R = \sum_{i=1}^{N} n_i \tag{A13}$$

Regional Mean (L_1^R) is unity using the index-flood procedure:

$$L_1^R = 1 \tag{A14}$$

Regional L-Cv (t_2^R):

$$t_2^R = n_R^{-1} \sum_{i=1}^{N} n_i \; t_2^i \tag{A15}$$

Regional L-Skewness (t_3^R):

$$t_3^R = n_R^{-1} \sum_{i=1}^{N} n_i \; t_3^i \tag{A16}$$

Regional L-Kurtosis (t_4^R):

$$t_4^R = n_R^{-1} \sum_{i=1}^{N} n_i \; t_4^i \tag{A17}$$

APPENDIX - B

SELECTED DEFINITIONS

SELECTED DEFINITIONS

The following terms are used in this report and are defined here for convenience of the reader.

Annual Exceedance Probability (AEP) - the probability that a given value for the phenomenon of interest will be equaled or exceeded in any given year.

At-Site - the term at-site is used in various ways. It may be used to distinguish analyses/data at a specific site from regional analyses/data. It may be used in reference to a given gage/station or a specific geographic location. Observed at-site precipitation is synonymous with observed point rainfall.

At-Site Mean - the mean value of precipitation for a specified duration at a specific location. For a gaged site, it is based on the mean of the annual maxima series data for the specified duration. At an ungaged site, it is usually based on statistical relationships.

Climatic Region - a geographic area that has similar physical and climatological characteristics.

Gage Mean - the mean value computed from the annual maxima data at a precipitation gage for some specified duration. At-site mean values are determined from gage mean values using minor correction factors to adjust from fixed measurement intervals to true intervals. See Weiss[22].

Gaged Site - a geographic location where a precipitation gage is used to measure and record precipitation data. See also ungaged site.

Homogeneous Region - a collection of sites/gages with similar physical and/or climatic characteristics that can be described by a common regional growth curve.

Inter-Duration - any duration of interest within a storm, other than the duration used for indexing the storm. For example, precipitation at the 24-hour duration is used for indexing long-duration design storms. Other durations of interest, such as 1-hr, 2-hr, 3-hr, 6-hr, 12-hr, etc., would be considered inter-durations for long-duration storms.

Mean Annual Precipitation (MAP) - the average precipitation for a calendar year based on either the period of record or the most recent 30-years of record ending on a decade. For example the period from 1971-2000 is the most recent 30-year climate normal period.

Regional - the term regional is used in a generic manner to distinguish data/analyses for a group of sites/gages as opposed to individual at-site data/analyses. The term regional may be used in reference to homogeneous sub-regions or climatic regions.

Recurrence Interval - the average time interval between occurrences of a hydrologic event of a given magnitude or larger (also termed return period). Usually measured in years.

Regional Growth Curve - a magnitude-frequency curve with a mean value of unity that is applicable to all sites within a homogeneous region .

Seasonality - frequency characteristics for the time of year (month) during which certain characteristics of precipitation have been observed to occur.

Ungaged Site - a geographic location where no precipitation measurements are available.

APPENDIX - C

CATALOG OF STORMS
USED FOR ANALYZING STORM CHARACTERISTICS

OVERVIEW

This appendix contains catalogs of the dates and locations of the occurrence of storms that were used for the analysis of storm characteristics for short, intermediate and long-duration storms. This includes precipitation events (storms) recorded at gages within the SPU gaging network and storms recorded at gages that are part of the NOAA national cooperative gaging network[13]. Storm dates and location observed at the NOAA gaging network were identified in a prior study by Schaefer[15].

Table C1 – Catalog of Storms used for Analyzing the Characteristics of Short-Duration Storms for the Seattle Metropolitan Area

STATION ID	STATION NAME	GAGE OPERATOR	YEARS RECORD	2-HR PRECIP (in)	MON	DAY	YEAR
45-7709	Skykomish 1 ENE	NOAA	60	1.78	5	25	1945
45-1277	Centralia 1 W	NOAA	60	1.15	10	28	1949
45-5224	McMillin Reservoir	NOAA	60	1.07	9	17	1957
45-2675	Everett	NOAA	60	1.14	5	31	1958
45-5224	McMillin Reservoir	NOAA	60	1.70	8	26	1960
45-4769	Longview	NOAA	47	1.05	8	23	1963
45-7773	Snoqualmie Falls	NOAA	47	1.17	9	19	1964
45-0986	Burlington	NOAA	60	1.28	8	12	1965
45-6678	Port Townsend	NOAA	30	0.84	9	10	1967
45-2675	Everett	NOAA	60	0.99	9	22	1972
45-1277	Centralia 1 W	NOAA	60	1.20	7	8	1974
45-7458	Seattle EMSU	NOAA	26	1.64	8	26	1977
45-1146	Carnation 4 NW	NOAA	60	1.20	9	20	1977
45-4486	Landsburg	NOAA	47	0.90	7	9	1980
45-S013	Aberdeen 20 NNE	NOAA	61	2.50	5	28	1982
45-S002	Mathews Beach Pump Stn	SPU	35	0.86	6	14	1978
45-S003	UW Hydraulics Lab	SPU	39	1.28	11	3	1978
45-S009	Woodland Park Zoo	SPU	39	0.89	8	17	1980
45-S008	Ballard Locks	SPU	39	0.90	8	28	1980
45-S002	Mathews Beach Pump Stn	SPU	35	0.74	5	29	1985
45-S014	West Seattle High School	SPU	39	0.85	10	26	1986
45-S020	TT Minor Elementary	SPU	29	0.88	10	4	1990
45-S009	Woodland Park Zoo	SPU	39	0.72	8	9	1991
45-S008	Ballard Locks	SPU	39	1.02	9	23	1992
45-S003	UW Hydraulics Lab	SPU	39	0.77	11	23	1997
45-S011	Metro-KC Denny Regulatng	SPU	34	0.84	2	17	1998
45-S016	Metro-KC E Marginal Way	SPU	34	0.71	7	15	2001
45-S012	Catherine Blaine Jr	SPU	39	0.84	8	23	2001
45-S020	TT Minor Elementary	SPU	29	0.83	5	28	2002
45-S009	Woodland Park Zoo	SPU	39	0.79	9	3	2002

Table C2 – Catalog of Storms used for Analyzing the Characteristics of Intermediate-Duration Storms for the Seattle Metropolitan Area

STATION ID	STATION NAME	GAGE OPERATOR	YEARS RECORD	6-HR PRECIP (in)	MON	DAY	YEAR
45-7488	Seattle WSO	NOAA	26	1.60	1	19	1943
45-6678	Port Townsend	NOAA	30	1.35	6	14	1946
45-7488	Seattle WSO	NOAA	26	1.50	2	16	1949
45-9485	Yelm	NOAA	39	1.44	11	20	1959
45-0729	Blaine 1 ENE	NOAA	60	1.60	11	3	1971
45-9485	Yelm	NOAA	39	1.43	12	21	1972
45-6624	Port Angeles	NOAA	60	1.92	11	3	1978
45-7458	Seattle EMSU	NOAA	26	1.56	12	3	1982
45-7773	Snoqualmie Falls	NOAA	47	2.00	1	23	1982
45-5224	McMillin Reservoir	NOAA	60	1.90	8	29	1983
45-0729	Blaine 1 ENE	NOAA	60	1.70	12	29	1983
45-0729	Blaine 1ENE	NOAA	60	2.00	2	15	1986
45-S008	Ballard Locks	SPU	39	1.52	1	18	1967
45-S008	Ballard Locks	SPU	39	1.60	12	3	1968
45-S009	Woodland Park Zoo	SPU	39	1.16	11	4	1969
45-S014	West Seattle High School	SPU	39	1.32	1	14	1971
45-S004	Maple Leaf Reservoir	SPU	39	1.12	2	26	1974
45-S001	Haller Lake Shop	SPU	39	1.74	11	4	1978
45-S016	Metro-KC E Marginal Way	SPU	34	1.61	9	22	1978
45-S003	UW Hydraulics Lab	SPU	39	1.82	12	3	1982
45-S001	Haller Lake Shop	SPU	39	1.21	9	5	1984
45-S020	TT Minor Elementary	SPU	29	2.27	1	18	1986
45-S010	Rainier Ave Elementary	SPU	36	1.83	1	9	1990
45-S003	UW Hydraulics Lab	SPU	39	1.44	12	29	1996
45-S004	Maple Leaf Reservoir	SPU	39	1.28	6	24	1999

Table C3 – Catalog of Storms used for Analyzing the Characteristics of Long-Duration Storms for the Seattle Metropolitan Area

STATION ID	STATION NAME	GAGE OPERATOR	YEARS RECORD	24-HR PRECIP (in)	MON	DAY	YEAR
45-1277	Centralia 1 W	NOAA	60	2.98	10	30	1942
45-0986	Burlington	NOAA	60	4.91	10	24	1945
45-7473	Sea-Tac Airport	NOAA	38	3.00	2	6	1945
45-0986	Burlington	NOAA	60	3.42	2	15	1949
45-6114	Olympia	NOAA	53	4.93	2	9	1951
45-0729	Blaine 1 ENE	NOAA	60	3.63	11	3	1955
45-0324	Auburn	NOAA	24	3.63	11	20	1959
45-6624	Port Angeles	NOAA	60	3.12	1	14	1961
45-4769	Longview	NOAA	47	5.41	11	19	1962
45-1191	Castle Rock	NOAA	25	4.62	11	23	1964
45-7773	Snoqualmie Falls	NOAA	47	4.72	1	18	1967
45-4769	Longview	NOAA	47	4.70	12	2	1977
45-7473	Sea-Tac Airport	NOAA	38	3.71	10	6	1981
45-7458	Seattle EMSU	NOAA	26	4.48	1	18	1986
45-4769	Longview	NOAA	47	4.70	2	23	1986
45-S008	Ballard Locks	SPU	39	3.74	3	4	1972
45-S008	Ballard Locks	SPU	39	2.31	12	17	1979
45-S009	Woodland Park Zoo	SPU	39	4.55	10	6	1981
45-S014	West Seattle High School	SPU	39	2.94	1	4	1983
45-S004	Maple Leaf Reservoir	SPU	39	2.51	11	1	1984
45-S001	Haller Lake Shop	SPU	39	5.07	1	18	1986
45-S016	Metro-KC E Marginal Way	SPU	34	3.00	11	23	1986
45-S003	UW Hydraulics Lab	SPU	39	2.97	11	24	1990
45-S001	Haller Lake Shop	SPU	39	2.91	4	4	1991
45-S020	TT Minor Elementary	SPU	29	2.91	2	8	1996
45-S010	Rainier Ave Elementary	SPU	36	3.00	4	3	1996
45-S003	UW Hydraulics Lab	SPU	39	3.03	3	18	1997
45-S004	Maple Leaf Reservoir	SPU	39	2.67	11	25	1998
45-S010	Rainier Ave Elementary	SPU	36	3.30	11	14	2001

APPENDIX - D

TABULAR VALUES OF DIMENSIONLESS DESIGN STORMS

OVERVIEW

This appendix contains tabular values of dimensionless design storms that were developed for the Seattle Metropolitan area. A suite of dimensionless design storms, representing a range of durations, were developed to capture the diversity in intensities and temporal patterns that are exhibited in storms in western Washington. These design storms are associated with storm types that may generally be categorized as short-duration, intermediate-duration, and long-duration storms (Schaefer[15]).

The short, intermediate, and long-duration design storms are scaled by precipitation amounts at the 2-hour, 6-hour and 24-hour durations, respectively (Table 7, main report). This approach allows preservation of the precipitation-frequency characteristics at these durations as well as preserving the characteristics of precipitation that may occur either prior or posterior to the duration used for scaling the design storm. In particular, this approach allows design storms to better replicate historical storms than methods commonly used in the past that artificially truncated historical storms to crop them to some pre-selected total storm duration.

A 24-hour design storm was also developed to meet the needs of certain stormwater regulations that require use of a 24-hour design storm. The 24-hour dimensionless design storm was developed based on the maximum 24-hour period of precipitation within the long-duration design storm. It has the same temporal shape and ordinates as the period of maximum 24-hour precipitation within the front-loaded and back-loaded long-duration dimensionless design storms.

Table 7 – Scaling of Dimensionless Design Storms

DESIGN STORM	DURATION OF PRECIPITATION USED FOR SCALING STORM	TOTALDURATION OF DESIGN STORM
Short	2-hour	3-hour
Intermediate	6-hour	18-hour
24-Hour (Appendix D)	24-hour	24-hour
Long	24-hour	64-hour

Short-Duration Dimensionless Design Storm

Short-duration design storms are typically used for design situations where peak discharge is of primary interest and there may be a need for a runoff hydrograph. Common applications include conveyance design of culverts and other hydraulic structures, and sizing of some water quality treatment facilities.

The design storm is obtained by scaling (multiplying) the ordinates of the dimensionless short-duration design storm (Table D-1, Figure 24) by the precipitation amount for the desired recurrence interval for the 2-hour duration. The resultant incremental precipitation ordinates have units of inches and the corresponding intensities (in/hr) may be obtained by multiplying the precipitation increments by 12.

Table D-1 – Dimensionless Ordinates of the Short-Duration Design Storm

DIMENSIONLESS ORDINATES OF SHORT-DURATION DESIGN STORM		
ELAPSED TIME (Min)	INCREMENTAL ORDINATES	CUMULATIVE ORDINATES
0	0.0000	0.0000
5	0.0045	0.0045
10	0.0055	0.0100
15	0.0075	0.0175
20	0.0086	0.0261
25	0.0102	0.0363
30	0.0134	0.0497
35	0.0173	0.0670
40	0.0219	0.0889
45	0.0272	0.1161
50	0.0331	0.1492
55	0.0364	0.1856
60	0.0434	0.2290
65	0.0553	0.2843
70	0.0659	0.3502
75	0.1200	0.4702
80	0.1900	0.6602
85	0.1000	0.7602
90	0.0512	0.8114
95	0.0472	0.8586
100	0.0398	0.8984
105	0.0301	0.9285
110	0.0244	0.9529
115	0.0195	0.9724
120	0.0153	0.9877
125	0.0125	1.0002
130	0.0096	1.0098
135	0.0077	1.0175
140	0.0068	1.0243
145	0.0062	1.0305
150	0.0056	1.0361
155	0.0050	1.0411
160	0.0044	1.0455
165	0.0038	1.0493
170	0.0032	1.0525
175	0.0026	1.0551
180	0.0020	1.0571

Intermediate-Duration Dimensionless Design Storm

Intermediate-duration design storms are used in design applications where both peak discharge and runoff volume are important considerations and there is a need for a runoff hydrograph.

The design storm is obtained by scaling (multiplying) the ordinates of the dimensionless intermediate-duration design storm (Table D-2, Figure 25) by the precipitation amount for the desired recurrence interval for the 6-hour duration. The resultant incremental precipitation ordinates have units of inches and the corresponding intensities (in/hr) may be obtained by multiplying the precipitation increments by 6.

Table D-2 – Dimensionless Ordinates of the Intermediate-Duration Design Storm

DIMENSIONLESS ORDINATES OF INTERMEDIATE-DURATION DESIGN STORM								
ELAPSED TIME (Min)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Min)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Min)	INCRM ORDINATE	SUM ORDINATE
0.00	0.0000	0.0000	6.17	0.0118	0.1972	12.17	0.0210	1.1731
0.17	0.0020	0.0020	6.33	0.0123	0.2095	12.33	0.0201	1.1932
0.33	0.0020	0.0040	6.50	0.0129	0.2224	12.50	0.0193	1.2125
0.50	0.0020	0.0060	6.67	0.0136	0.2360	12.67	0.0184	1.2309
0.67	0.0020	0.0080	6.83	0.0142	0.2502	12.83	0.0176	1.2485
0.83	0.0020	0.0100	7.00	0.0150	0.2652	13.00	0.0168	1.2653
1.00	0.0021	0.0121	7.17	0.0163	0.2815	13.17	0.0154	1.2807
1.17	0.0021	0.0142	7.33	0.0171	0.2986	13.33	0.0147	1.2954
1.33	0.0021	0.0163	7.50	0.0180	0.3166	13.50	0.0140	1.3094
1.50	0.0021	0.0184	7.67	0.0188	0.3354	13.67	0.0132	1.3226
1.67	0.0021	0.0205	7.83	0.0197	0.3551	13.83	0.0127	1.3353
1.83	0.0022	0.0227	8.00	0.0205	0.3756	14.00	0.0121	1.3474
2.00	0.0022	0.0249	8.17	0.0215	0.3971	14.17	0.0116	1.3590
2.17	0.0023	0.0272	8.33	0.0224	0.4195	14.33	0.0113	1.3703
2.33	0.0023	0.0295	8.50	0.0229	0.4424	14.50	0.0111	1.3814
2.50	0.0024	0.0319	8.67	0.0232	0.4656	14.67	0.0109	1.3923
2.67	0.0025	0.0344	8.83	0.0237	0.4893	14.83	0.0107	1.4030
2.83	0.0028	0.0372	9.00	0.0257	0.5150	15.00	0.0105	1.4135
3.00	0.0030	0.0402	9.17	0.0290	0.5440	15.17	0.0103	1.4238
3.17	0.0034	0.0436	9.33	0.0320	0.5760	15.33	0.0098	1.4336
3.33	0.0038	0.0474	9.50	0.0338	0.6098	15.50	0.0093	1.4429
3.50	0.0042	0.0516	9.67	0.0349	0.6447	15.67	0.0085	1.4514
3.67	0.0046	0.0562	9.83	0.0411	0.6858	15.83	0.0078	1.4592
3.83	0.0054	0.0616	10.00	0.0540	0.7398	16.00	0.0070	1.4662
4.00	0.0062	0.0678	10.17	0.0760	0.8158	16.17	0.0062	1.4724
4.17	0.0070	0.0748	10.33	0.0470	0.8628	16.33	0.0054	1.4778
4.33	0.0079	0.0827	10.50	0.0372	0.9000	16.50	0.0049	1.4827
4.50	0.0085	0.0912	10.67	0.0347	0.9347	16.67	0.0044	1.4871
4.67	0.0090	0.1002	10.83	0.0337	0.9684	16.83	0.0039	1.4910
4.83	0.0095	0.1097	11.00	0.0330	1.0014	17.00	0.0035	1.4945
5.00	0.0100	0.1197	11.17	0.0308	1.0322	17.17	0.0032	1.4977
5.17	0.0104	0.1301	11.33	0.0269	1.0591	17.33	0.0029	1.5006
5.33	0.0107	0.1408	11.50	0.0247	1.0838	17.50	0.0026	1.5032
5.50	0.0109	0.1517	11.67	0.0237	1.1075	17.67	0.0024	1.5056
5.67	0.0110	0.1627	11.83	0.0228	1.1303	17.83	0.0024	1.5080
5.83	0.0113	0.1740	12.00	0.0218	1.1521	18.00	0.0023	1.5103
6.00	0.0114	0.1854						

Long-Duration Dimensionless Design Storm
Long-duration design storms are primarily used in design of stormwater detention facilities and other projects where runoff volume is a primary consideration. Two long-duration dimensionless design storms are provided: a front-loaded design storm (Table D-3, Figure 26a) with the highest intensities at the beginning of the storm; and a back-loaded storm (Table D-4, Figure 26b) with the higher intensities nearer the end of the storm period. The front-loaded design storm is seen somewhat more frequently (Table 12a), however the back-loaded storm is a more practical event (more conservative) for stormwater facility design.

The design storm is obtained by scaling (multiplying) the ordinates of the dimensionless long-duration design storm (Tables D-3, D-4) by the precipitation amount for the desired recurrence interval for the 24-hour duration. The resultant incremental precipitation ordinates have units of inches and the corresponding intensities (in/hr) may be obtained by multiplying the precipitation increments by 6.

Table D-3 – Dimensionless Ordinates of Front-Loaded Long-Duration Design Storm

DIMENSIONLESS ORDINATES OF FRONT-LOADED LONG-DURATION DESIGN STORM								
ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE
0.00	0.0000	0.0000	7.17	0.0018	0.0569	14.17	0.0072	0.2570
0.17	0.0001	0.0001	7.33	0.0019	0.0588	14.33	0.0073	0.2643
0.33	0.0003	0.0004	7.50	0.0019	0.0607	14.50	0.0074	0.2717
0.50	0.0005	0.0009	7.67	0.0020	0.0627	14.67	0.0075	0.2792
0.67	0.0007	0.0016	7.83	0.0022	0.0649	14.83	0.0076	0.2868
0.83	0.0009	0.0025	8.00	0.0024	0.0673	15.00	0.0077	0.2945
1.00	0.0010	0.0035	8.17	0.0026	0.0699	15.17	0.0078	0.3023
1.17	0.0011	0.0046	8.33	0.0028	0.0727	15.33	0.0078	0.3101
1.33	0.0012	0.0058	8.50	0.0030	0.0757	15.50	0.0078	0.3179
1.50	0.0013	0.0071	8.67	0.0032	0.0789	15.67	0.0079	0.3258
1.67	0.0013	0.0084	8.83	0.0034	0.0823	15.83	0.0079	0.3337
1.83	0.0013	0.0097	9.00	0.0036	0.0859	16.00	0.0079	0.3416
2.00	0.0013	0.0110	9.17	0.0038	0.0897	16.17	0.0081	0.3497
2.17	0.0013	0.0123	9.33	0.0040	0.0937	16.33	0.0082	0.3579
2.33	0.0013	0.0136	9.50	0.0042	0.0979	16.50	0.0082	0.3661
2.50	0.0014	0.0150	9.67	0.0045	0.1024	16.67	0.0093	0.3754
2.67	0.0014	0.0164	9.83	0.0047	0.1071	16.83	0.0099	0.3853
2.83	0.0014	0.0178	10.00	0.0048	0.1119	17.00	0.0102	0.3955
3.00	0.0014	0.0192	10.17	0.0049	0.1168	17.17	0.0104	0.4059
3.17	0.0014	0.0206	10.33	0.0049	0.1217	17.33	0.0107	0.4166
3.33	0.0014	0.0220	10.50	0.0049	0.1266	17.50	0.0114	0.4280
3.50	0.0014	0.0234	10.67	0.0050	0.1316	17.67	0.0118	0.4398
3.67	0.0014	0.0248	10.83	0.0051	0.1367	17.83	0.0142	0.4540
3.83	0.0014	0.0262	11.00	0.0051	0.1418	18.00	0.0220	0.4760
4.00	0.0014	0.0276	11.17	0.0053	0.1471	18.17	0.0290	0.5050
4.17	0.0014	0.0290	11.33	0.0053	0.1524	18.33	0.0160	0.5210
4.33	0.0015	0.0305	11.50	0.0054	0.1578	18.50	0.0127	0.5337
4.50	0.0015	0.0320	11.67	0.0054	0.1632	18.67	0.0116	0.5453
4.67	0.0015	0.0335	11.83	0.0054	0.1686	18.83	0.0110	0.5563
4.83	0.0015	0.0350	12.00	0.0055	0.1741	19.00	0.0106	0.5669
5.00	0.0015	0.0365	12.17	0.0055	0.1796	19.17	0.0102	0.5771
5.17	0.0015	0.0380	12.33	0.0056	0.1852	19.33	0.0096	0.5867
5.33	0.0015	0.0395	12.50	0.0057	0.1909	19.50	0.0082	0.5949
5.50	0.0015	0.0410	12.67	0.0058	0.1967	19.67	0.0082	0.6031
5.67	0.0015	0.0425	12.83	0.0060	0.2027	19.83	0.0082	0.6113
5.83	0.0015	0.0440	13.00	0.0062	0.2089	20.00	0.0081	0.6194
6.00	0.0015	0.0455	13.17	0.0064	0.2153	20.17	0.0080	0.6274
6.17	0.0015	0.0470	13.33	0.0066	0.2219	20.33	0.0079	0.6353
6.33	0.0015	0.0485	13.50	0.0068	0.2287	20.50	0.0079	0.6432
6.50	0.0016	0.0501	13.67	0.0069	0.2356	20.67	0.0078	0.6510
6.67	0.0016	0.0517	13.83	0.0070	0.2426	20.83	0.0078	0.6588
6.83	0.0017	0.0534	14.00	0.0072	0.2498	21.00	0.0077	0.6665
7.00	0.0017	0.0551						

Table D-3 – Dimensionless Ordinates of Front-Loaded Long-Duration Design Storm (continued)

DIMENSIONLESS ORDINATES OF FRONT-LOADED LONG-DURATION DESIGN STORM								
ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE
21.17	0.0077	0.6742	30.17	0.0050	1.0069	39.17	0.0000	1.0984
21.33	0.0077	0.6819	30.33	0.0049	1.0118	39.33	0.0000	1.0984
21.50	0.0077	0.6896	30.50	0.0049	1.0167	39.50	0.0000	1.0984
21.67	0.0076	0.6972	30.67	0.0049	1.0216	39.67	0.0000	1.0984
21.83	0.0075	0.7047	30.83	0.0049	1.0265	39.83	0.0000	1.0984
22.00	0.0075	0.7122	31.00	0.0048	1.0313	40.00	0.0000	1.0984
22.17	0.0074	0.7196	31.17	0.0048	1.0361	40.17	0.0000	1.0984
22.33	0.0074	0.7270	31.33	0.0048	1.0409	40.33	0.0000	1.0984
22.50	0.0073	0.7343	31.50	0.0047	1.0456	40.50	0.0000	1.0984
22.67	0.0073	0.7416	31.67	0.0046	1.0502	40.67	0.0000	1.0984
22.83	0.0073	0.7489	31.83	0.0045	1.0547	40.83	0.0000	1.0984
23.00	0.0072	0.7561	32.00	0.0044	1.0591	41.00	0.0000	1.0984
23.17	0.0072	0.7633	32.17	0.0043	1.0634	41.17	0.0000	1.0984
23.33	0.0072	0.7705	32.33	0.0042	1.0676	41.33	0.0000	1.0984
23.50	0.0071	0.7776	32.50	0.0041	1.0717	41.50	0.0000	1.0984
23.67	0.0071	0.7847	32.67	0.0039	1.0756	41.67	0.0000	1.0984
23.83	0.0070	0.7917	32.83	0.0038	1.0794	41.83	0.0000	1.0984
24.00	0.0070	0.7987	33.00	0.0037	1.0831	42.00	0.0000	1.0984
24.17	0.0069	0.8056	33.17	0.0033	1.0864	42.17	0.0000	1.0984
24.33	0.0068	0.8124	33.33	0.0029	1.0893	42.33	0.0000	1.0984
24.50	0.0067	0.8191	33.50	0.0025	1.0918	42.50	0.0000	1.0984
24.67	0.0067	0.8258	33.67	0.0021	1.0939	42.67	0.0000	1.0984
24.83	0.0066	0.8324	33.83	0.0017	1.0956	42.83	0.0000	1.0984
25.00	0.0065	0.8389	34.00	0.0013	1.0969	43.00	0.0000	1.0984
25.17	0.0062	0.8451	34.17	0.0009	1.0978	43.17	0.0000	1.0984
25.33	0.0062	0.8513	34.33	0.0005	1.0983	43.33	0.0000	1.0984
25.50	0.0060	0.8573	34.50	0.0001	1.0984	43.50	0.0000	1.0984
25.67	0.0059	0.8632	34.67	0.0000	1.0984	43.67	0.0000	1.0984
25.83	0.0059	0.8691	34.83	0.0000	1.0984	43.83	0.0000	1.0984
26.00	0.0058	0.8749	35.00	0.0000	1.0984	44.00	0.0000	1.0984
26.17	0.0057	0.8806	35.17	0.0000	1.0984	44.17	0.0000	1.0984
26.33	0.0056	0.8862	35.33	0.0000	1.0984	44.33	0.0000	1.0984
26.50	0.0055	0.8917	35.50	0.0000	1.0984	44.50	0.0000	1.0984
26.67	0.0055	0.8972	35.67	0.0000	1.0984	44.67	0.0000	1.0984
26.83	0.0055	0.9027	35.83	0.0000	1.0984	44.83	0.0000	1.0984
27.00	0.0055	0.9082	36.00	0.0000	1.0984	45.00	0.0000	1.0984
27.17	0.0054	0.9136	36.17	0.0000	1.0984	45.17	0.0000	1.0984
27.33	0.0054	0.9190	36.33	0.0000	1.0984	45.33	0.0000	1.0984
27.50	0.0054	0.9244	36.50	0.0000	1.0984	45.50	0.0000	1.0984
27.67	0.0053	0.9297	36.67	0.0000	1.0984	45.67	0.0000	1.0984
27.83	0.0053	0.9350	36.83	0.0000	1.0984	45.83	0.0000	1.0984
28.00	0.0053	0.9403	37.00	0.0000	1.0984	46.00	0.0000	1.0984
28.17	0.0053	0.9456	37.17	0.0000	1.0984	46.17	0.0000	1.0984
28.33	0.0052	0.9508	37.33	0.0000	1.0984	46.33	0.0000	1.0984
28.50	0.0052	0.9560	37.50	0.0000	1.0984	46.50	0.0000	1.0984
28.67	0.0052	0.9612	37.67	0.0000	1.0984	46.67	0.0000	1.0984
28.83	0.0052	0.9664	37.83	0.0000	1.0984	46.83	0.0000	1.0984
29.00	0.0052	0.9716	38.00	0.0000	1.0984	47.00	0.0000	1.0984
29.17	0.0051	0.9767	38.17	0.0000	1.0984	47.17	0.0000	1.0984
29.33	0.0051	0.9818	38.33	0.0000	1.0984	47.33	0.0000	1.0984
29.50	0.0051	0.9869	38.50	0.0000	1.0984	47.50	0.0000	1.0984
29.67	0.0050	0.9919	38.67	0.0000	1.0984	47.67	0.0001	1.0985
29.83	0.0050	0.9969	38.83	0.0000	1.0984	47.83	0.0002	1.0987
30.00	0.0050	1.0019	39.00	0.0000	1.0984	48.00	0.0003	1.0990

Table D-3 – Dimensionless Ordinates of Front-Loaded Long-Duration Design Storm (continued)

DIMENSIONLESS ORDINATES OF FRONT-LOADED LONG-DURATION DESIGN STORM								
ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE
48.17	0.0004	1.0994	56.17	0.0026	1.2422			
48.33	0.0005	1.0999	56.33	0.0024	1.2446			
48.50	0.0006	1.1005	56.50	0.0023	1.2469			
48.67	0.0007	1.1012	56.67	0.0023	1.2492			
48.83	0.0007	1.1019	56.83	0.0022	1.2514			
49.00	0.0007	1.1026	57.00	0.0021	1.2535			
49.17	0.0007	1.1033	57.17	0.0019	1.2554			
49.33	0.0007	1.1040	57.33	0.0017	1.2571			
49.50	0.0007	1.1047	57.50	0.0016	1.2587			
49.67	0.0007	1.1054	57.67	0.0015	1.2602			
49.83	0.0007	1.1061	57.83	0.0015	1.2617			
50.00	0.0007	1.1068	58.00	0.0015	1.2632			
50.17	0.0007	1.1075	58.17	0.0015	1.2647			
50.33	0.0008	1.1083	58.33	0.0015	1.2662			
50.50	0.0009	1.1092	58.50	0.0015	1.2677			
50.67	0.0010	1.1102	58.67	0.0014	1.2691			
50.83	0.0011	1.1113	58.83	0.0014	1.2705			
51.00	0.0012	1.1125	59.00	0.0013	1.2718			
51.17	0.0013	1.1138	59.17	0.0013	1.2731			
51.33	0.0014	1.1152	59.33	0.0012	1.2743			
51.50	0.0014	1.1166	59.50	0.0012	1.2755			
51.67	0.0014	1.1180	59.67	0.0011	1.2766			
51.83	0.0014	1.1194	59.83	0.0010	1.2776			
52.00	0.0015	1.1209	60.00	0.0009	1.2785			
52.17	0.0016	1.1225	60.17	0.0009	1.2794			
52.33	0.0018	1.1243	60.33	0.0008	1.2802			
52.50	0.0020	1.1263	60.50	0.0008	1.2810			
52.67	0.0021	1.1284	60.67	0.0007	1.2817			
52.83	0.0023	1.1307	60.83	0.0007	1.2824			
53.00	0.0023	1.1330	61.00	0.0007	1.2831			
53.17	0.0024	1.1354	61.17	0.0007	1.2838			
53.33	0.0026	1.1380	61.33	0.0007	1.2845			
53.50	0.0028	1.1408	61.50	0.0007	1.2852			
53.67	0.0032	1.1440	61.67	0.0007	1.2859			
53.83	0.0039	1.1479	61.83	0.0007	1.2866			
54.00	0.0048	1.1527	62.00	0.0007	1.2873			
54.17	0.0056	1.1583	62.17	0.0007	1.2880			
54.33	0.0076	1.1659	62.33	0.0007	1.2887			
54.50	0.0096	1.1755	62.50	0.0007	1.2894			
54.67	0.0133	1.1888	62.67	0.0006	1.2900			
54.83	0.0133	1.2021	62.83	0.0005	1.2905			
55.00	0.0096	1.2117	63.00	0.0004	1.2909			
55.17	0.0076	1.2193	63.17	0.0003	1.2912			
55.33	0.0056	1.2249	63.33	0.0002	1.2914			
55.50	0.0048	1.2297	63.50	0.0001	1.2915			
55.67	0.0039	1.2336	63.67	0.0000	1.2915			
55.83	0.0032	1.2368	63.83	0.0000	1.2915			
56.00	0.0028	1.2396	64.00	0.0000	1.2915			

Table D-4 – Dimensionless Ordinates of Back-Loaded Long-Duration Design Storm

DIMENSIONLESS ORDINATES OF BACK-LOADED LONG-DURATION DESIGN STORM								
ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE
0.00	0.0000	0.0000	8.17	0.0039	0.1352	16.17	0.0000	0.1931
0.17	0.0001	0.0001	8.33	0.0032	0.1384	16.33	0.0000	0.1931
0.33	0.0002	0.0003	8.50	0.0028	0.1412	16.50	0.0000	0.1931
0.50	0.0003	0.0006	8.67	0.0026	0.1438	16.67	0.0000	0.1931
0.67	0.0004	0.0010	8.83	0.0024	0.1462	16.83	0.0000	0.1931
0.83	0.0005	0.0015	9.00	0.0023	0.1485	17.00	0.0000	0.1931
1.00	0.0006	0.0021	9.17	0.0023	0.1508	17.17	0.0000	0.1931
1.17	0.0007	0.0028	9.33	0.0022	0.1530	17.33	0.0000	0.1931
1.33	0.0007	0.0035	9.50	0.0021	0.1551	17.50	0.0000	0.1931
1.50	0.0007	0.0042	9.67	0.0019	0.1570	17.67	0.0000	0.1931
1.67	0.0007	0.0049	9.83	0.0017	0.1587	17.83	0.0000	0.1931
1.83	0.0007	0.0056	10.00	0.0016	0.1603	18.00	0.0000	0.1931
2.00	0.0007	0.0063	10.17	0.0015	0.1618	18.17	0.0000	0.1931
2.17	0.0007	0.0070	10.33	0.0015	0.1633	18.33	0.0000	0.1931
2.33	0.0007	0.0077	10.50	0.0015	0.1648	18.50	0.0000	0.1931
2.50	0.0007	0.0084	10.67	0.0015	0.1663	18.67	0.0000	0.1931
2.67	0.0007	0.0091	10.83	0.0015	0.1678	18.83	0.0000	0.1931
2.83	0.0008	0.0099	11.00	0.0015	0.1693	19.00	0.0000	0.1931
3.00	0.0009	0.0108	11.17	0.0014	0.1707	19.17	0.0000	0.1931
3.17	0.0010	0.0118	11.33	0.0014	0.1721	19.33	0.0000	0.1931
3.33	0.0011	0.0129	11.50	0.0013	0.1734	19.50	0.0000	0.1931
3.50	0.0012	0.0141	11.67	0.0013	0.1747	19.67	0.0000	0.1931
3.67	0.0013	0.0154	11.83	0.0012	0.1759	19.83	0.0000	0.1931
3.83	0.0014	0.0168	12.00	0.0012	0.1771	20.00	0.0000	0.1931
4.00	0.0014	0.0182	12.17	0.0011	0.1782	20.17	0.0000	0.1931
4.17	0.0014	0.0196	12.33	0.0010	0.1792	20.33	0.0000	0.1931
4.33	0.0014	0.0210	12.50	0.0009	0.1801	20.50	0.0000	0.1931
4.50	0.0015	0.0225	12.67	0.0009	0.1810	20.67	0.0000	0.1931
4.67	0.0016	0.0241	12.83	0.0008	0.1818	20.83	0.0000	0.1931
4.83	0.0018	0.0259	13.00	0.0008	0.1826	21.00	0.0000	0.1931
5.00	0.0020	0.0279	13.17	0.0007	0.1833	21.17	0.0000	0.1931
5.17	0.0021	0.0300	13.33	0.0007	0.1840	21.33	0.0000	0.1931
5.33	0.0023	0.0323	13.50	0.0007	0.1847	21.50	0.0000	0.1931
5.50	0.0023	0.0346	13.67	0.0007	0.1854	21.67	0.0000	0.1931
5.67	0.0024	0.0370	13.83	0.0007	0.1861	21.83	0.0000	0.1931
5.83	0.0026	0.0396	14.00	0.0007	0.1868	22.00	0.0000	0.1931
6.00	0.0028	0.0424	14.17	0.0007	0.1875	22.17	0.0000	0.1931
6.17	0.0032	0.0456	14.33	0.0007	0.1882	22.33	0.0000	0.1931
6.33	0.0039	0.0495	14.50	0.0007	0.1889	22.50	0.0000	0.1931
6.50	0.0048	0.0543	14.67	0.0007	0.1896	22.67	0.0000	0.1931
6.67	0.0056	0.0599	14.83	0.0007	0.1903	22.83	0.0000	0.1931
6.83	0.0076	0.0675	15.00	0.0007	0.1910	23.00	0.0000	0.1931
7.00	0.0096	0.0771	15.17	0.0006	0.1916	23.17	0.0000	0.1931
7.17	0.0133	0.0904	15.33	0.0005	0.1921	23.33	0.0000	0.1931
7.33	0.0133	0.1037	15.50	0.0004	0.1925	23.50	0.0000	0.1931
7.50	0.0096	0.1133	15.67	0.0003	0.1928	23.67	0.0000	0.1931
7.67	0.0076	0.1209	15.83	0.0002	0.1930	23.83	0.0000	0.1931
7.83	0.0056	0.1265	16.00	0.0001	0.1931	24.00	0.0000	0.1931
8.00	0.0048	0.1313						

Table D-4 – Dimensionless Ordinates of Back-Loaded Long-Duration Design Storm (continued)

DIMENSIONLESS ORDINATES OF BACK-LOADED LONG-DURATION DESIGN STORM								
ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE
24.17	0.0000	0.1931	32.17	0.0014	0.2137	40.17	0.0053	0.3402
24.33	0.0000	0.1931	32.33	0.0014	0.2151	40.33	0.0053	0.3455
24.50	0.0000	0.1931	32.50	0.0014	0.2165	40.50	0.0054	0.3509
24.67	0.0000	0.1931	32.67	0.0014	0.2179	40.67	0.0054	0.3563
24.83	0.0000	0.1931	32.83	0.0014	0.2193	40.83	0.0054	0.3617
25.00	0.0000	0.1931	33.00	0.0014	0.2207	41.00	0.0055	0.3672
25.17	0.0000	0.1931	33.17	0.0014	0.2221	41.17	0.0055	0.3727
25.33	0.0000	0.1931	33.33	0.0015	0.2236	41.33	0.0056	0.3783
25.50	0.0000	0.1931	33.50	0.0015	0.2251	41.50	0.0057	0.3840
25.67	0.0000	0.1931	33.67	0.0015	0.2266	41.67	0.0058	0.3898
25.83	0.0000	0.1931	33.83	0.0015	0.2281	41.83	0.0060	0.3958
26.00	0.0000	0.1931	34.00	0.0015	0.2296	42.00	0.0062	0.4020
26.17	0.0000	0.1931	34.17	0.0015	0.2311	42.17	0.0064	0.4084
26.33	0.0000	0.1931	34.33	0.0015	0.2326	42.33	0.0066	0.4150
26.50	0.0000	0.1931	34.50	0.0015	0.2341	42.50	0.0068	0.4218
26.67	0.0000	0.1931	34.67	0.0015	0.2356	42.67	0.0069	0.4287
26.83	0.0000	0.1931	34.83	0.0015	0.2371	42.83	0.0070	0.4357
27.00	0.0000	0.1931	35.00	0.0015	0.2386	43.00	0.0072	0.4429
27.17	0.0000	0.1931	35.17	0.0015	0.2401	43.17	0.0072	0.4501
27.33	0.0000	0.1931	35.33	0.0015	0.2416	43.33	0.0073	0.4574
27.50	0.0000	0.1931	35.50	0.0016	0.2432	43.50	0.0074	0.4648
27.67	0.0000	0.1931	35.67	0.0016	0.2448	43.67	0.0075	0.4723
27.83	0.0000	0.1931	35.83	0.0017	0.2465	43.83	0.0076	0.4799
28.00	0.0000	0.1931	36.00	0.0017	0.2482	44.00	0.0077	0.4876
28.17	0.0000	0.1931	36.17	0.0018	0.2500	44.17	0.0078	0.4954
28.33	0.0000	0.1931	36.33	0.0019	0.2519	44.33	0.0078	0.5032
28.50	0.0000	0.1931	36.50	0.0019	0.2538	44.50	0.0078	0.5110
28.67	0.0000	0.1931	36.67	0.0020	0.2558	44.67	0.0079	0.5189
28.83	0.0000	0.1931	36.83	0.0022	0.2580	44.83	0.0079	0.5268
29.00	0.0000	0.1931	37.00	0.0024	0.2604	45.00	0.0079	0.5347
29.17	0.0001	0.1932	37.17	0.0026	0.2630	45.17	0.0081	0.5428
29.33	0.0003	0.1935	37.33	0.0028	0.2658	45.33	0.0082	0.5510
29.50	0.0005	0.1940	37.50	0.0030	0.2688	45.50	0.0082	0.5592
29.67	0.0007	0.1947	37.67	0.0032	0.2720	45.67	0.0093	0.5685
29.83	0.0009	0.1956	37.83	0.0034	0.2754	45.83	0.0099	0.5784
30.00	0.0010	0.1966	38.00	0.0036	0.2790	46.00	0.0102	0.5886
30.17	0.0011	0.1977	38.17	0.0038	0.2828	46.17	0.0104	0.5990
30.33	0.0012	0.1989	38.33	0.0040	0.2868	46.33	0.0107	0.6097
30.50	0.0013	0.2002	38.50	0.0042	0.2910	46.50	0.0114	0.6211
30.67	0.0013	0.2015	38.67	0.0045	0.2955	46.67	0.0118	0.6329
30.83	0.0013	0.2028	38.83	0.0047	0.3002	46.83	0.0142	0.6471
31.00	0.0013	0.2041	39.00	0.0048	0.3050	47.00	0.0220	0.6691
31.17	0.0013	0.2054	39.17	0.0049	0.3099	47.17	0.0290	0.6981
31.33	0.0013	0.2067	39.33	0.0049	0.3148	47.33	0.0160	0.7141
31.50	0.0014	0.2081	39.50	0.0049	0.3197	47.50	0.0127	0.7268
31.67	0.0014	0.2095	39.67	0.0050	0.3247	47.67	0.0116	0.7384
31.83	0.0014	0.2109	39.83	0.0051	0.3298	47.83	0.0110	0.7494
32.00	0.0014	0.2123	40.00	0.0051	0.3349	48.00	0.0106	0.7600

Table D-4 – Dimensionless Ordinates of Back-Loaded Long-Duration Design Storm (continued)

DIMENSIONLESS ORDINATES OF BACK-LOADED LONG-DURATION DESIGN STORM								
ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE
48.17	0.0102	0.7702	56.17	0.0054	1.1067			
48.33	0.0096	0.7798	56.33	0.0054	1.1121			
48.50	0.0082	0.7880	56.50	0.0054	1.1175			
48.67	0.0082	0.7962	56.67	0.0053	1.1228			
48.83	0.0082	0.8044	56.83	0.0053	1.1281			
49.00	0.0081	0.8125	57.00	0.0053	1.1334			
49.17	0.0080	0.8205	57.17	0.0053	1.1387			
49.33	0.0079	0.8284	57.33	0.0052	1.1439			
49.50	0.0079	0.8363	57.50	0.0052	1.1491			
49.67	0.0078	0.8441	57.67	0.0052	1.1543			
49.83	0.0078	0.8519	57.83	0.0052	1.1595			
50.00	0.0077	0.8596	58.00	0.0052	1.1647			
50.17	0.0077	0.8673	58.17	0.0051	1.1698			
50.33	0.0077	0.8750	58.33	0.0051	1.1749			
50.50	0.0077	0.8827	58.50	0.0051	1.1800			
50.67	0.0076	0.8903	58.67	0.0050	1.1850			
50.83	0.0075	0.8978	58.83	0.0050	1.1900			
51.00	0.0075	0.9053	59.00	0.0050	1.1950			
51.17	0.0074	0.9127	59.17	0.0050	1.2000			
51.33	0.0074	0.9201	59.33	0.0049	1.2049			
51.50	0.0073	0.9274	59.50	0.0049	1.2098			
51.67	0.0073	0.9347	59.67	0.0049	1.2147			
51.83	0.0073	0.9420	59.83	0.0049	1.2196			
52.00	0.0072	0.9492	60.00	0.0048	1.2244			
52.17	0.0072	0.9564	60.17	0.0048	1.2292			
52.33	0.0072	0.9636	60.33	0.0048	1.2340			
52.50	0.0071	0.9707	60.50	0.0047	1.2387			
52.67	0.0071	0.9778	60.67	0.0046	1.2433			
52.83	0.0070	0.9848	60.83	0.0045	1.2478			
53.00	0.0070	0.9918	61.00	0.0044	1.2522			
53.17	0.0069	0.9987	61.17	0.0043	1.2565			
53.33	0.0068	1.0055	61.33	0.0042	1.2607			
53.50	0.0067	1.0122	61.50	0.0041	1.2648			
53.67	0.0067	1.0189	61.67	0.0039	1.2687			
53.83	0.0066	1.0255	61.83	0.0038	1.2725			
54.00	0.0065	1.0320	62.00	0.0037	1.2762			
54.17	0.0062	1.0382	62.17	0.0033	1.2795			
54.33	0.0062	1.0444	62.33	0.0029	1.2824			
54.50	0.0060	1.0504	62.50	0.0025	1.2849			
54.67	0.0059	1.0563	62.67	0.0021	1.2870			
54.83	0.0059	1.0622	62.83	0.0017	1.2887			
55.00	0.0058	1.0680	63.00	0.0013	1.2900			
55.17	0.0057	1.0737	63.17	0.0009	1.2909			
55.33	0.0056	1.0793	63.33	0.0005	1.2914			
55.50	0.0055	1.0848	63.50	0.0001	1.2915			
55.67	0.0055	1.0903	63.67	0.0000	1.2915			
55.83	0.0055	1.0958	63.83	0.0000	1.2915			
56.00	0.0055	1.1013	64.00	0.0000	1.2915			

24-Hour Dimensionless Design Storm

Some existing regulations and policies require the use of a 24-hour design storm for specific stormwater applications. To meet this need, the 24-hour dimensionless design storm was developed based on the maximum 24-hour period of precipitation within the long-duration design storm. In should be noted that the 24-hour dimensionless design storm has the same temporal shape and ordinates as the period of maximum 24-hour precipitation within the front-loaded and back-loaded long-duration dimensionless design storms.

The 24-hour design storm is obtained by scaling (multiplying) the ordinates of the dimensionless 24-hour design storm (Table D-5, Figure D-1) by the precipitation amount for the desired recurrence interval for the 24-hour duration. The resultant incremental precipitation ordinates have units of inches and the corresponding intensities (in/hr) may be obtained by multiplying the precipitation increments by 6.

Table D-5 – Dimensionless Ordinates of 24-Hour Design Storm

DIMENSIONLESS ORDINATES OF 24-HOUR DESIGN STORM								
ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE
0.00	0.0000	0.0000	7.17	0.0080	0.2596	14.17	0.0072	0.6769
0.17	0.0036	0.0036	7.33	0.0082	0.2678	14.33	0.0072	0.6841
0.33	0.0038	0.0074	7.50	0.0084	0.2762	14.50	0.0072	0.6913
0.50	0.0040	0.0114	7.67	0.0088	0.2850	14.67	0.0071	0.6984
0.67	0.0042	0.0156	7.83	0.0093	0.2943	14.83	0.0071	0.7055
0.83	0.0045	0.0201	8.00	0.0099	0.3042	15.00	0.0070	0.7125
1.00	0.0047	0.0248	8.17	0.0102	0.3144	15.17	0.0070	0.7195
1.17	0.0048	0.0296	8.33	0.0104	0.3248	15.33	0.0069	0.7264
1.33	0.0049	0.0345	8.50	0.0107	0.3355	15.50	0.0068	0.7332
1.50	0.0049	0.0394	8.67	0.0114	0.3469	15.67	0.0067	0.7399
1.67	0.0049	0.0443	8.83	0.0127	0.3596	15.83	0.0066	0.7465
1.83	0.0050	0.0493	9.00	0.0142	0.3738	16.00	0.0065	0.7530
2.00	0.0051	0.0544	9.17	0.0220	0.3958	16.17	0.0064	0.7594
2.17	0.0051	0.0595	9.33	0.0290	0.4248	16.33	0.0063	0.7657
2.33	0.0053	0.0648	9.50	0.0160	0.4408	16.50	0.0062	0.7719
2.50	0.0053	0.0701	9.67	0.0127	0.4535	16.67	0.0060	0.7779
2.67	0.0054	0.0755	9.83	0.0116	0.4651	16.83	0.0059	0.7838
2.83	0.0054	0.0809	10.00	0.0110	0.4761	17.00	0.0059	0.7897
3.00	0.0054	0.0863	10.17	0.0106	0.4867	17.17	0.0058	0.7955
3.17	0.0055	0.0918	10.33	0.0102	0.4969	17.33	0.0057	0.8012
3.33	0.0055	0.0973	10.50	0.0096	0.5065	17.50	0.0056	0.8068
3.50	0.0056	0.1029	10.67	0.0089	0.5154	17.67	0.0055	0.8123
3.67	0.0057	0.1086	10.83	0.0085	0.5239	17.83	0.0055	0.8178
3.83	0.0058	0.1144	11.00	0.0083	0.5322	18.00	0.0055	0.8233
4.00	0.0060	0.1204	11.17	0.0082	0.5404	18.17	0.0055	0.8288
4.17	0.0062	0.1266	11.33	0.0081	0.5485	18.33	0.0054	0.8342
4.33	0.0064	0.1330	11.50	0.0080	0.5565	18.50	0.0054	0.8396
4.50	0.0066	0.1396	11.67	0.0079	0.5644	18.67	0.0054	0.8450
4.67	0.0068	0.1464	11.83	0.0078	0.5722	18.83	0.0053	0.8503
4.83	0.0069	0.1533	12.00	0.0078	0.5800	19.00	0.0053	0.8556
5.00	0.0070	0.1603	12.17	0.0077	0.5877	19.17	0.0053	0.8609
5.17	0.0072	0.1675	12.33	0.0077	0.5954	19.33	0.0053	0.8662
5.33	0.0072	0.1747	12.50	0.0076	0.6030	19.50	0.0052	0.8714
5.50	0.0073	0.1820	12.67	0.0076	0.6106	19.67	0.0052	0.8766
5.67	0.0074	0.1894	12.83	0.0075	0.6181	19.83	0.0052	0.8818
5.83	0.0075	0.1969	13.00	0.0075	0.6256	20.00	0.0052	0.8870
6.00	0.0076	0.2045	13.17	0.0074	0.6330	20.17	0.0052	0.8922
6.17	0.0077	0.2122	13.33	0.0074	0.6404	20.33	0.0051	0.8973
6.33	0.0078	0.2200	13.50	0.0074	0.6478	20.50	0.0051	0.9024
6.50	0.0078	0.2278	13.67	0.0073	0.6551	20.67	0.0051	0.9075
6.67	0.0079	0.2357	13.83	0.0073	0.6624	20.83	0.0050	0.9125
6.83	0.0079	0.2436	14.00	0.0073	0.6697	21.00	0.0050	0.9175
7.00	0.0080	0.2516						

Table D-5 – Dimensionless Ordinates of 24-Hour Design Storm (continued)

DIMENSIONLESS ORDINATES OF 24-HOUR DESIGN STORM								
ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE	ELAPSED TIME (Hr)	INCRM ORDINATE	SUM ORDINATE
21.17	0.0050	0.9225						
21.33	0.0050	0.9275						
21.50	0.0049	0.9324						
21.67	0.0049	0.9373						
21.83	0.0049	0.9422						
22.00	0.0049	0.9471						
22.17	0.0048	0.9519						
22.33	0.0048	0.9567						
22.50	0.0048	0.9615						
22.67	0.0047	0.9662						
22.83	0.0046	0.9708						
23.00	0.0045	0.9753						
23.17	0.0044	0.9797						
23.33	0.0043	0.9840						
23.50	0.0042	0.9882						
23.67	0.0041	0.9923						
23.83	0.0039	0.9962						
24.00	0.0038	1.0000						

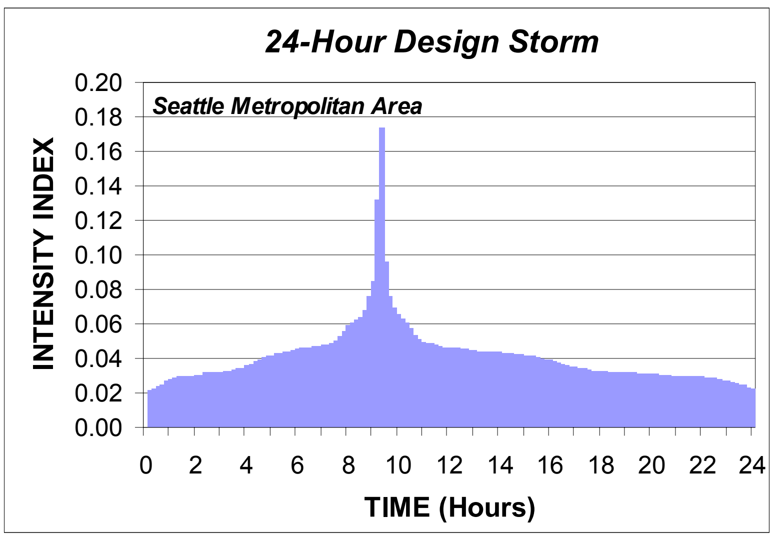


Figure D-1 – Dimensionless 24-Hour Design Storm for Seattle Metropolitan Area

APPENDIX E

PRECIPITATION MAGNITUDE-FREQUENCY ESTIMATES FOR SPU GAGE LOCATIONS

OVERVIEW

This appendix contains estimates of precipitation-frequency values for durations of 6-hr, 12-hr, 24-hr, 48-hr, 72-hr, and 7-days for locations of SPU precipitation gages (Table E-1a) in both tabular format and as magnitude-frequency curves. These precipitation values are based on estimates of the at-site mean values for the location of SPU gages (Table E-1b) based on the spatial analysis of precipitation (gridded datasets) and the applicable regional growth curves obtained from the regional frequency analyses. Corrections (Langbein[9], Equation 4) have been applied to provide equivalent partial duration series estimates for frequently occurring events (5 times/year, 2 times/year, once/year, 2-year and 5-year recurrence intervals).

Table E-1a – Listing of City of Seattle (SPU) Precipitation Gages

STATION ID	STATION NAME	LATITUDE	LONGITUDE	YEAR START	YEAR END	GAGE TYPE
45-S001	Haller Lake Shop	47.7211	122.3431	1965	2003	TB
45-S002	Mathews Beach Pump Station	47.6950	122.2731	1969	2003	TB
45-S003	UW Hydraulics Lab	47.6481	122.3081	1965	2003	TB
45-S004	Maple Leaf Reservoir	47.6900	122.3119	1965	2003	TB
45-S005	Fauntleroy Ferry Dock	47.5231	122.3919	1968	2003	TB
45-S007	Whitman Middle School	47.6961	122.3769	1965	2003	TB
45-S008	Ballard Locks	47.6650	122.3969	1965	2003	TB
45-S009	Woodland Park Zoo	47.6681	122.3539	1965	2003	TB
45-S010	Rainier Ave Elementary	47.5000	122.2600	1968	2003	TB
45-S011	Metro-KC Denny Regulating	47.6169	122.3550	1970	2003	TB
45-S012	Catherine Blaine Jr	47.6419	122.3969	1965	2003	TB
45-S014	West Seattle High School	47.5781	122.3819	1965	2003	TB
45-S015	Metro-KC Diagonal Pump	47.5619	122.3400	1965	2003	TB
45-S016	Metro-KC E Marginal Way	47.5350	122.3139	1970	2003	TB
45-S017	West Seattle Engr Shop	47.5211	122.3450	1965	2003	TB
45-S018	Hillman Engr Shop	47.5481	122.2750	1965	2003	TB
45-S020	TT Minor Elementary	47.6119	122.3069	1975	2003	TB
45-7473	Seattle Tacoma Airport	47.4500	122.3000	1965	2002	HR

Table E-1b – Listing of At-Site Mean Values for City of Seattle (SPU) Precipitation Gages

AT-SITE MEAN VALUES (in)							
STATION ID	STATION NAME	6-HR	12-HR	24-HR	48-HR	72-HR	7-DAY
45-S001	Haller Lake Shop	1.00	1.44	1.87	2.56	2.91	4.10
45-S002	Mathews Beach Pump Station	1.00	1.43	1.85	2.55	2.89	4.07
45-S003	UW Hydraulics Lab	1.01	1.45	1.90	2.60	2.95	4.18
45-S004	Maple Leaf Reservoir	1.00	1.44	1.87	2.57	2.91	4.11
45-S005	Fauntleroy Ferry Dock	1.06	1.58	2.14	2.89	3.32	4.80
45-S007	Whitman Middle School	1.01	1.45	1.89	2.59	2.94	4.16
45-S008	Ballard Locks	1.03	1.50	1.99	2.71	3.08	4.41
45-S009	Woodland Park Zoo	1.01	1.45	1.89	2.59	2.94	4.16
45-S010	Rainier Ave Elementary	1.02	1.47	1.94	2.65	3.01	4.28
45-S011	Metro-KC Denny Regulating	1.01	1.46	1.91	2.61	2.97	4.21
45-S012	Catherine Blaine Jr	1.03	1.50	1.99	2.71	3.09	4.41
45-S014	West Seattle High School	1.03	1.51	2.00	2.73	3.11	4.44
45-S015	Metro-KC Diagonal Pump	1.01	1.46	1.91	2.61	2.96	4.20
45-S016	Metro-KC E Marginal Way	1.02	1.47	1.94	2.65	3.02	4.29
45-S017	West Seattle Engr Shop	1.03	1.51	2.02	2.74	3.13	4.48
45-S018	Hillman Engr Shop	1.01	1.46	1.91	2.61	2.97	4.21
45-S020	TT Minor Elementary	1.00	1.44	1.88	2.58	2.92	4.12
45-7473	Seattle Tacoma Airport	1.04	1.54	2.06	2.80	3.20	4.60

Table E-2, Figure E-2 – Precipitation-Magnitude-Frequency Estimates for Location of SPU Gage 01

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.58	0.75	0.88	1.02	1.20	1.33	1.48	1.52	1.67	1.82
12	0.76	1.05	1.26	1.47	1.76	1.96	2.19	2.27	2.49	2.72
24	0.93	1.32	1.61	1.91	2.31	2.61	2.94	3.04	3.37	3.71
48	1.34	1.84	2.22	2.61	3.14	3.53	3.97	4.11	4.56	5.02
72	1.53	2.11	2.53	2.97	3.56	3.98	4.47	4.62	5.10	5.58
168	2.11	3.00	3.62	4.23	5.01	5.53	6.10	6.28	6.81	7.32

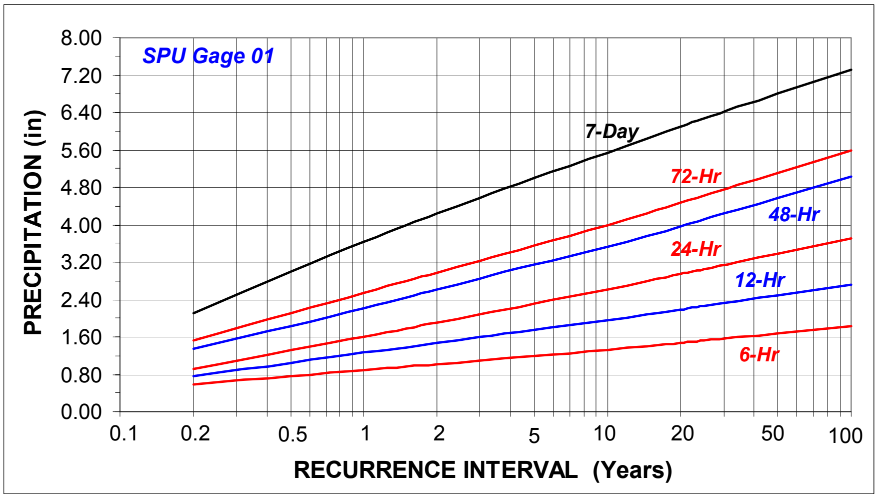


Table E-3, Figure E-3 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 02

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.58	0.75	0.88	1.02	1.20	1.33	1.48	1.52	1.67	1.82
12	0.76	1.04	1.25	1.46	1.75	1.95	2.18	2.25	2.48	2.70
24	0.92	1.31	1.59	1.89	2.29	2.58	2.90	3.01	3.34	3.67
48	1.33	1.83	2.21	2.60	3.13	3.51	3.95	4.10	4.55	5.00
72	1.52	2.09	2.51	2.95	3.54	3.96	4.43	4.59	5.06	5.55
168	2.09	2.98	3.60	4.20	4.97	5.49	6.06	6.23	6.76	7.27

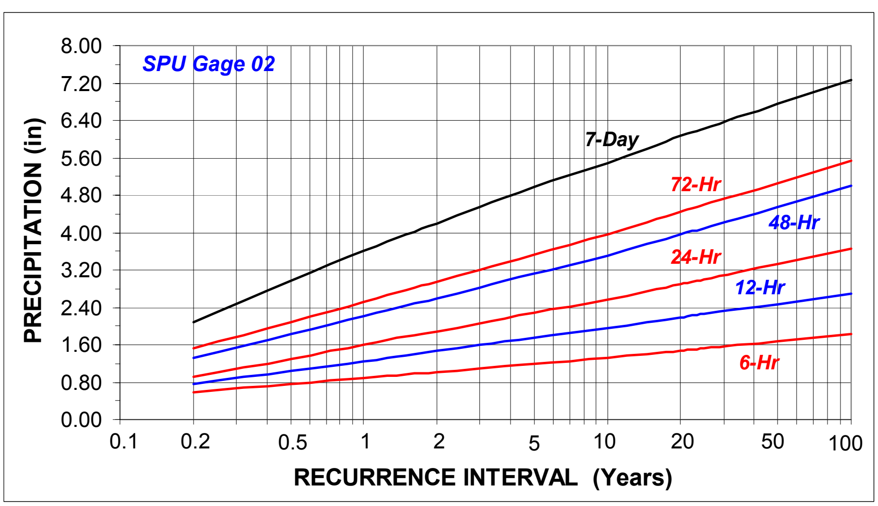


Table E-4, Figure E-4 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 03

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.58	0.76	0.89	1.03	1.21	1.34	1.49	1.54	1.69	1.84
12	0.77	1.06	1.27	1.48	1.77	1.97	2.21	2.28	2.51	2.74
24	0.94	1.34	1.64	1.94	2.35	2.65	2.98	3.09	3.43	3.77
48	1.36	1.87	2.25	2.65	3.19	3.58	4.03	4.18	4.63	5.10
72	1.55	2.14	2.57	3.01	3.61	4.04	4.53	4.68	5.17	5.66
168	2.15	3.06	3.69	4.32	5.10	5.64	6.22	6.40	6.94	7.47

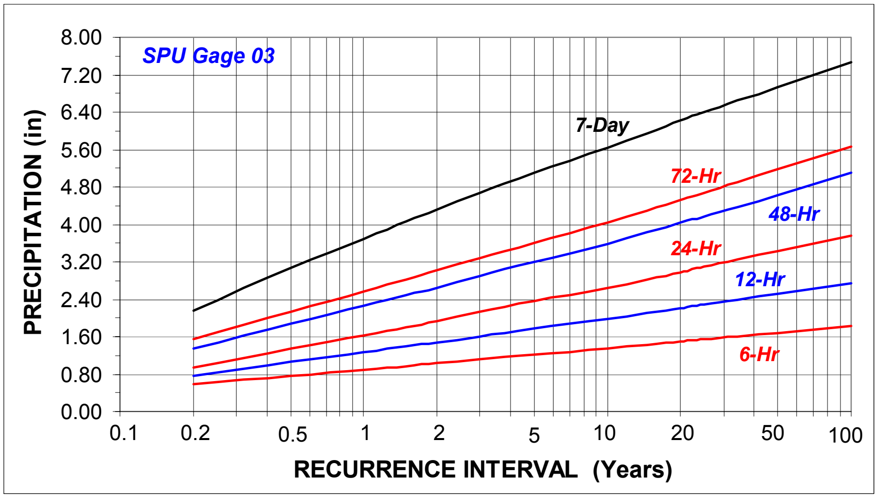


Table E-5, Figure E-5 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 04

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.58	0.75	0.88	1.02	1.20	1.33	1.48	1.52	1.67	1.82
12	0.76	1.05	1.26	1.47	1.76	1.96	2.19	2.27	2.49	2.72
24	0.93	1.32	1.61	1.91	2.31	2.61	2.94	3.04	3.37	3.71
48	1.34	1.85	2.22	2.62	3.15	3.54	3.99	4.13	4.58	5.04
72	1.53	2.11	2.53	2.97	3.56	3.98	4.47	4.62	5.10	5.58
168	2.11	3.01	3.63	4.24	5.02	5.55	6.12	6.29	6.83	7.34

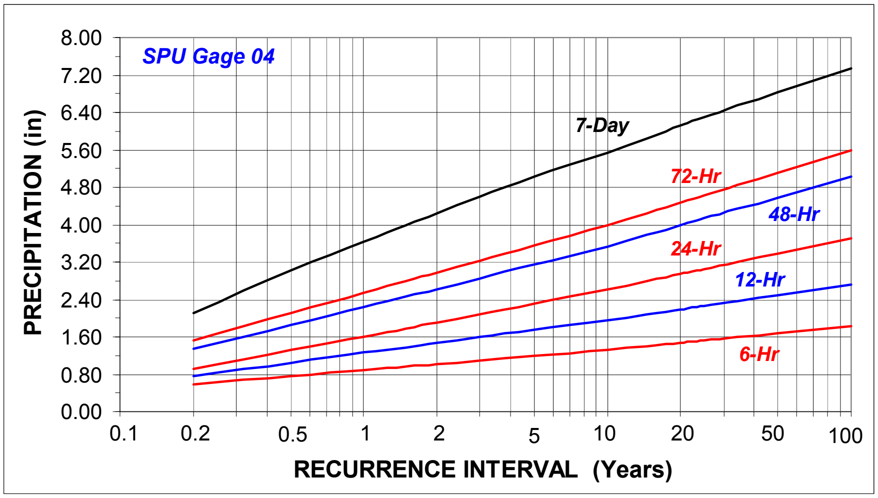


Table E-6, Figure E-6 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 05

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.61	0.80	0.94	1.08	1.27	1.41	1.57	1.62	1.77	1.93
12	0.84	1.15	1.38	1.61	1.93	2.15	2.40	2.49	2.74	2.99
24	1.06	1.51	1.84	2.19	2.65	2.98	3.36	3.48	3.86	4.24
48	1.51	2.08	2.50	2.94	3.54	3.98	4.48	4.64	5.15	5.67
72	1.74	2.40	2.89	3.39	4.06	4.55	5.09	5.27	5.82	6.37
168	2.47	3.52	4.24	4.96	5.86	6.48	7.14	7.35	7.97	8.57

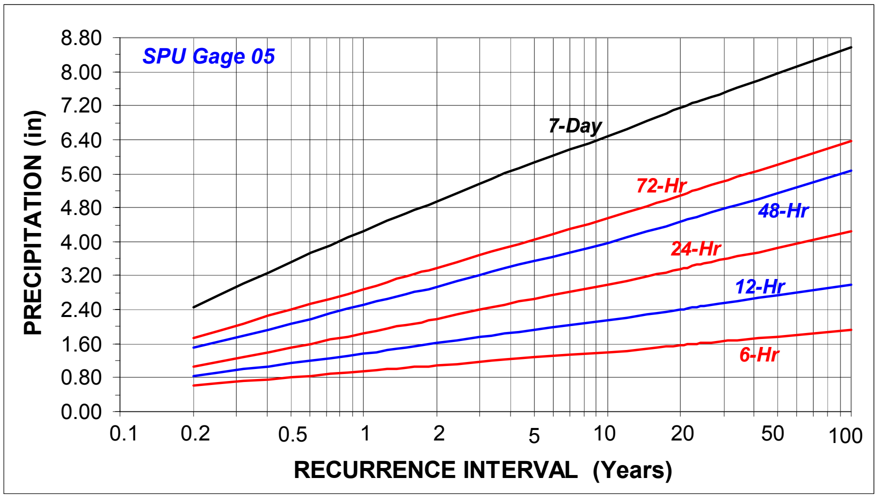


Table E-7, Figure E-7 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 07

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.58	0.76	0.89	1.03	1.21	1.34	1.49	1.54	1.69	1.84
12	0.77	1.06	1.27	1.48	1.77	1.97	2.21	2.28	2.51	2.74
24	0.94	1.33	1.63	1.93	2.34	2.63	2.97	3.07	3.41	3.75
48	1.35	1.86	2.24	2.64	3.18	3.57	4.02	4.16	4.62	5.08
72	1.54	2.13	2.56	3.00	3.60	4.03	4.51	4.67	5.15	5.64
168	2.14	3.05	3.68	4.30	5.08	5.61	6.19	6.37	6.91	7.43

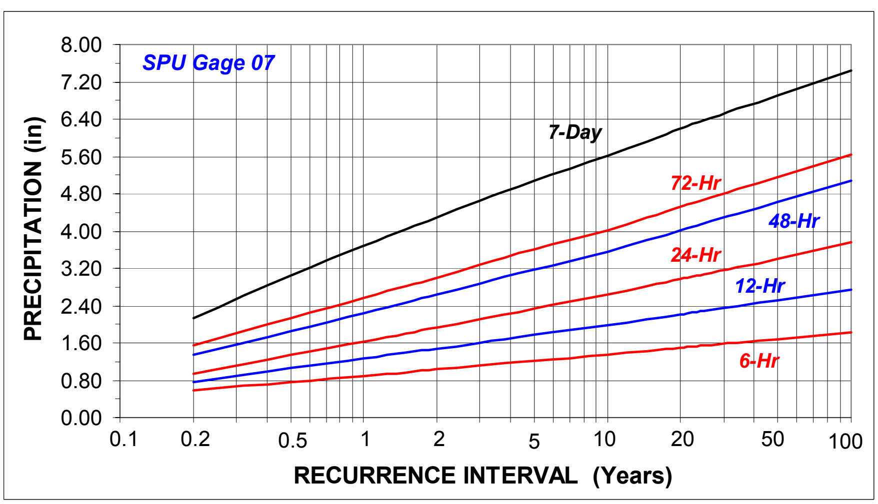


Table E-8, Figure E-8 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 08

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.59	0.78	0.91	1.05	1.24	1.37	1.52	1.57	1.72	1.87
12	0.80	1.09	1.31	1.53	1.83	2.04	2.28	2.36	2.60	2.84
24	0.98	1.41	1.71	2.03	2.46	2.77	3.12	3.24	3.59	3.94
48	1.41	1.95	2.35	2.76	3.32	3.73	4.20	4.35	4.83	5.32
72	1.62	2.23	2.68	3.14	3.77	4.22	4.73	4.89	5.40	5.91
168	2.27	3.23	3.90	4.55	5.39	5.95	6.56	6.75	7.33	7.88

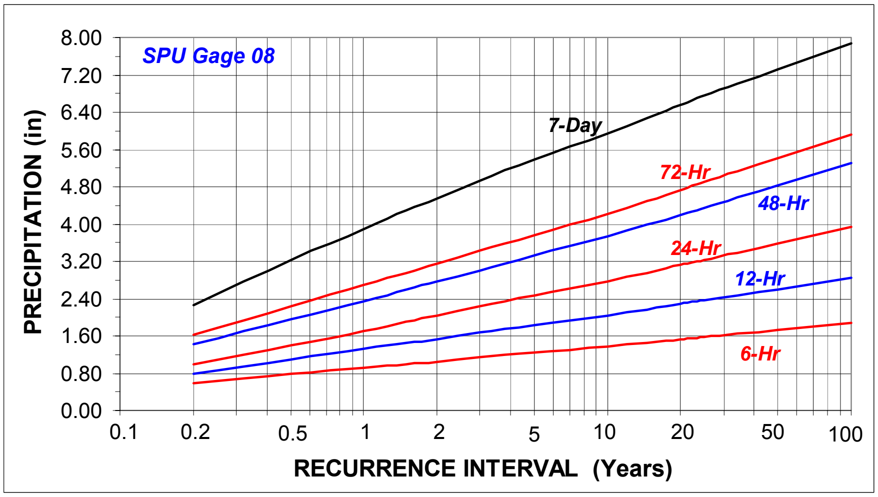


Table E-9, Figure E-9 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 09

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.58	0.76	0.89	1.03	1.21	1.34	1.49	1.54	1.69	1.84
12	0.77	1.06	1.27	1.48	1.77	1.97	2.21	2.28	2.51	2.74
24	0.94	1.33	1.63	1.93	2.34	2.63	2.97	3.07	3.41	3.75
48	1.35	1.86	2.24	2.64	3.18	3.57	4.02	4.16	4.62	5.08
72	1.54	2.13	2.56	3.00	3.60	4.03	4.51	4.67	5.15	5.64
168	2.14	3.05	3.68	4.30	5.08	5.61	6.19	6.37	6.91	7.43

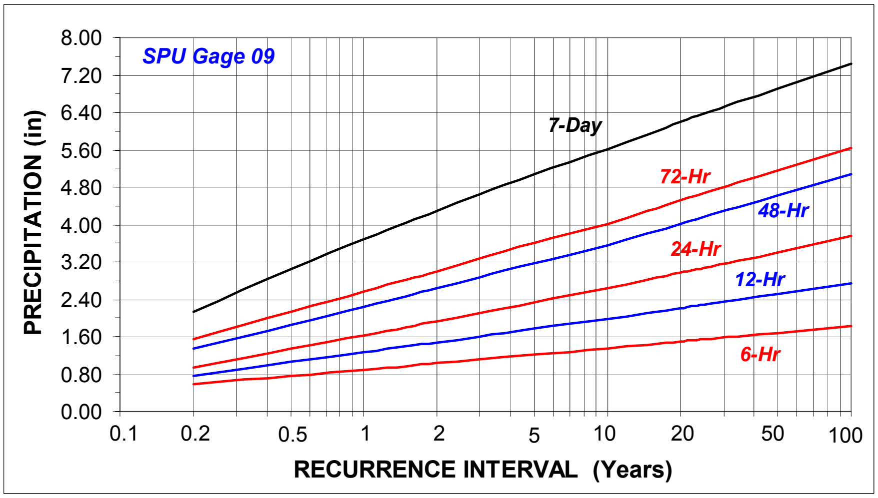


Table E-10, Figure E-10 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 10

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	**0.5-YR**	**1-YR**	**2-YR**	**5-YR**	**10-YR**	**20-YR**	**25-YR**	**50-YR**	**100-YR**
6	0.59	0.77	0.90	1.04	1.22	1.36	1.51	1.55	1.70	1.86
12	0.78	1.07	1.28	1.50	1.79	2.00	2.24	2.31	2.55	2.78
24	0.96	1.37	1.67	1.98	2.40	2.70	3.05	3.16	3.50	3.85
48	1.38	1.91	2.29	2.70	3.25	3.65	4.11	4.26	4.72	5.20
72	1.58	2.18	2.62	3.07	3.68	4.12	4.62	4.78	5.27	5.78
168	2.20	3.14	3.78	4.42	5.23	5.78	6.37	6.55	7.11	7.64

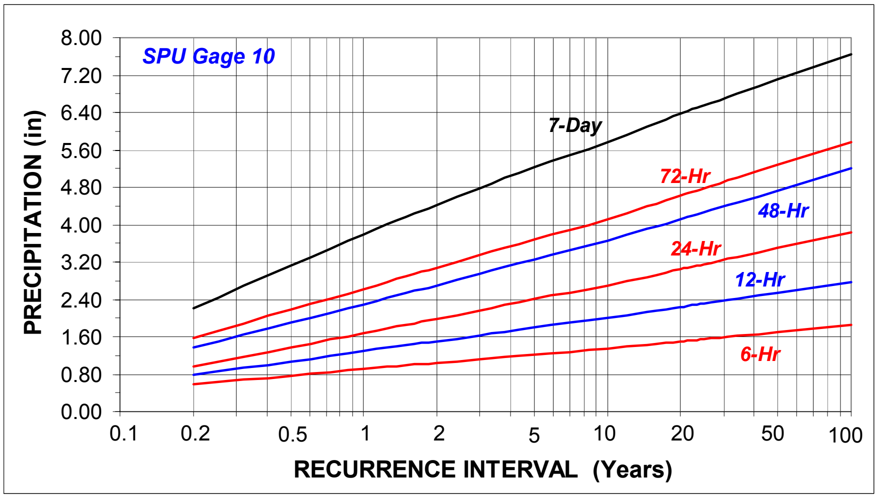


Table E-11, Figure E-11 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 11

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	**0.5-YR**	**1-YR**	**2-YR**	**5-YR**	**10-YR**	**20-YR**	**25-YR**	**50-YR**	**100-YR**
6	0.58	0.76	0.89	1.03	1.21	1.34	1.49	1.54	1.69	1.84
12	0.77	1.06	1.27	1.49	1.78	1.99	2.22	2.30	2.53	2.76
24	0.95	1.35	1.64	1.95	2.36	2.66	3.00	3.11	3.44	3.79
48	1.36	1.88	2.26	2.66	3.20	3.60	4.05	4.19	4.65	5.12
72	1.56	2.15	2.58	3.03	3.63	4.07	4.56	4.71	5.20	5.70
168	2.16	3.08	3.72	4.35	5.14	5.68	6.27	6.45	6.99	7.52

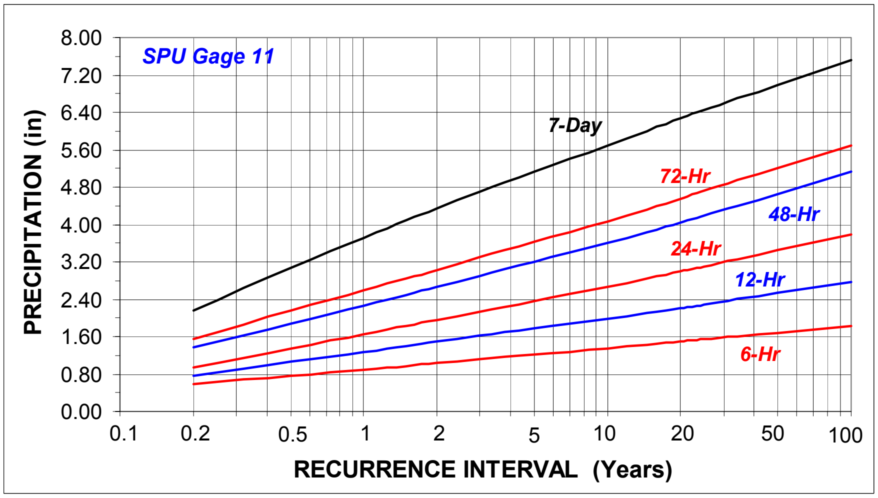


Table E-12, Figure E-12 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 12

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.59	0.78	0.91	1.05	1.24	1.37	1.52	1.57	1.72	1.87
12	0.80	1.09	1.31	1.53	1.83	2.04	2.28	2.36	2.60	2.84
24	0.98	1.41	1.71	2.03	2.46	2.77	3.12	3.24	3.59	3.94
48	1.41	1.95	2.35	2.76	3.32	3.73	4.20	4.35	4.83	5.32
72	1.62	2.24	2.69	3.16	3.78	4.23	4.74	4.90	5.41	5.93
168	2.27	3.23	3.90	4.55	5.39	5.95	6.56	6.75	7.33	7.88

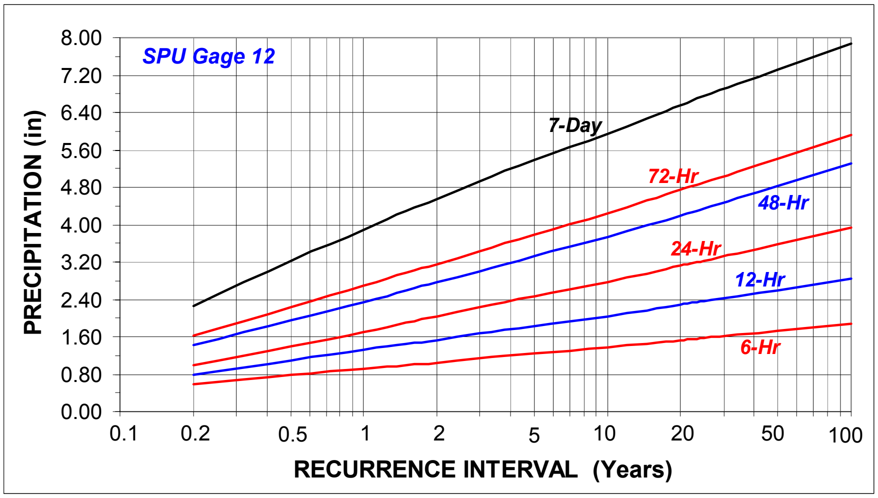


Table E-13, Figure E-13 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 14

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.59	0.78	0.91	1.05	1.24	1.37	1.52	1.57	1.72	1.87
12	0.80	1.10	1.32	1.54	1.84	2.06	2.30	2.38	2.61	2.86
24	0.99	1.41	1.72	2.04	2.48	2.79	3.14	3.25	3.61	3.96
48	1.42	1.96	2.36	2.78	3.35	3.76	4.23	4.39	4.87	5.36
72	1.63	2.25	2.71	3.18	3.81	4.26	4.77	4.94	5.45	5.97
168	2.28	3.25	3.92	4.58	5.42	5.99	6.61	6.80	7.38	7.93

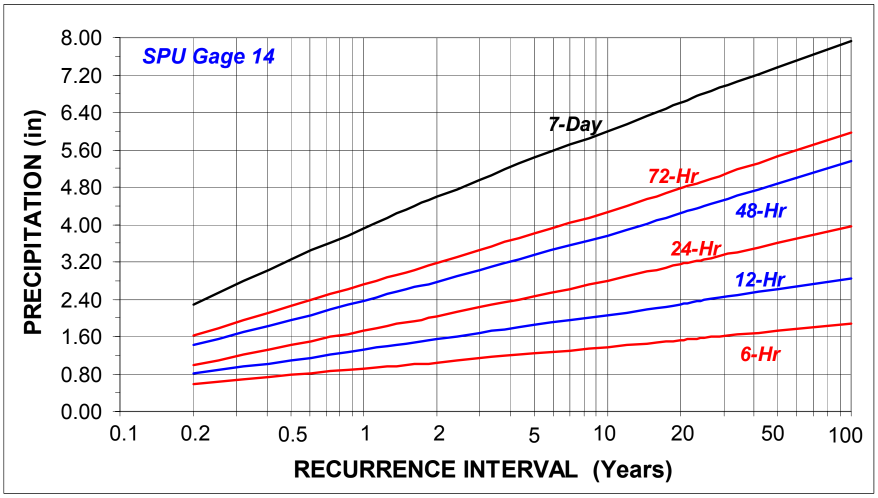


Table E-14, Figure E-14 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 15

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.58	0.76	0.89	1.03	1.21	1.34	1.49	1.54	1.69	1.84
12	0.77	1.06	1.27	1.49	1.78	1.99	2.22	2.30	2.53	2.76
24	0.95	1.35	1.64	1.95	2.36	2.66	3.00	3.11	3.44	3.79
48	1.36	1.88	2.26	2.66	3.20	3.60	4.05	4.19	4.65	5.12
72	1.55	2.14	2.58	3.02	3.62	4.05	4.54	4.70	5.19	5.68
168	2.16	3.08	3.71	4.34	5.13	5.67	6.25	6.43	6.98	7.50

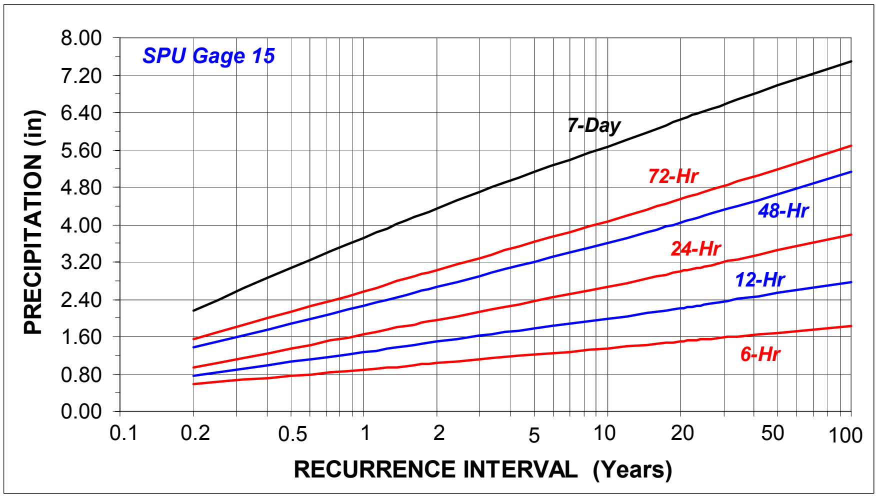


Table E-15, Figure E-15 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 16

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.59	0.77	0.90	1.04	1.22	1.36	1.51	1.55	1.70	1.86
12	0.78	1.07	1.28	1.50	1.79	2.00	2.24	2.31	2.55	2.78
24	0.96	1.37	1.67	1.98	2.40	2.70	3.05	3.16	3.50	3.85
48	1.38	1.91	2.29	2.70	3.25	3.65	4.11	4.26	4.72	5.20
72	1.58	2.19	2.63	3.08	3.70	4.13	4.63	4.79	5.29	5.80
168	2.20	3.14	3.79	4.43	5.24	5.79	6.39	6.57	7.13	7.66

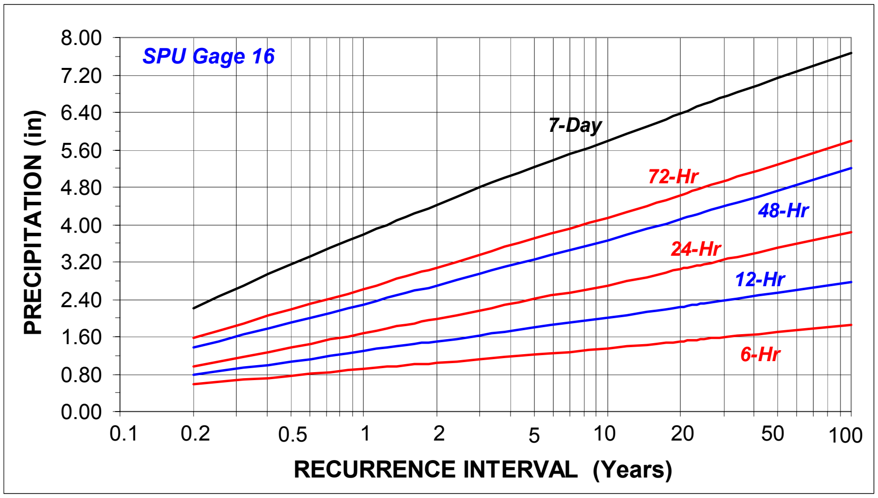


Table E-16, Figure E-16 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 17

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.59	0.78	0.91	1.05	1.24	1.37	1.52	1.57	1.72	1.87
12	0.80	1.10	1.32	1.54	1.84	2.06	2.30	2.38	2.61	2.86
24	1.00	1.43	1.74	2.06	2.50	2.81	3.17	3.29	3.64	4.00
48	1.43	1.97	2.37	2.79	3.36	3.77	4.25	4.40	4.88	5.37
72	1.64	2.27	2.72	3.20	3.83	4.29	4.80	4.97	5.49	6.01
168	2.30	3.28	3.96	4.63	5.47	6.05	6.67	6.86	7.44	8.00

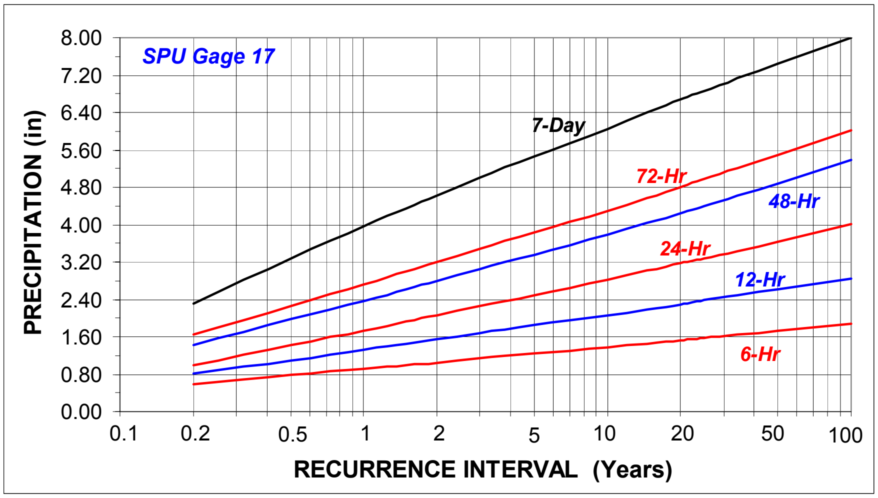


Table E-17, Figure E-17 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 18

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.58	0.76	0.89	1.03	1.21	1.34	1.49	1.54	1.69	1.84
12	0.77	1.06	1.27	1.49	1.78	1.99	2.22	2.30	2.53	2.76
24	0.95	1.35	1.64	1.95	2.36	2.66	3.00	3.11	3.44	3.79
48	1.36	1.88	2.26	2.66	3.20	3.60	4.05	4.19	4.65	5.12
72	1.56	2.15	2.58	3.03	3.63	4.07	4.56	4.71	5.20	5.70
168	2.16	3.08	3.72	4.35	5.14	5.68	6.27	6.45	6.99	7.52

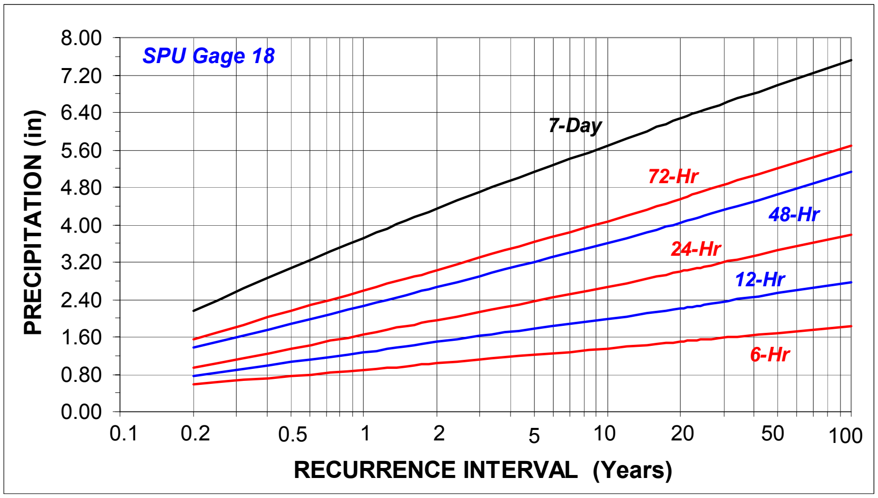


Table E-18, Figure E-18 – Precipitation-Magnitude-Frequency Estimates for SPU Gage 20

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.58	0.75	0.88	1.02	1.20	1.33	1.48	1.52	1.67	1.82
12	0.76	1.05	1.26	1.47	1.76	1.96	2.19	2.27	2.49	2.72
24	0.93	1.33	1.62	1.92	2.33	2.62	2.95	3.06	3.39	3.73
48	1.35	1.86	2.23	2.63	3.16	3.55	4.00	4.15	4.60	5.06
72	1.53	2.11	2.54	2.98	3.57	4.00	4.48	4.64	5.12	5.60
168	2.12	3.02	3.64	4.25	5.03	5.56	6.13	6.31	6.84	7.36

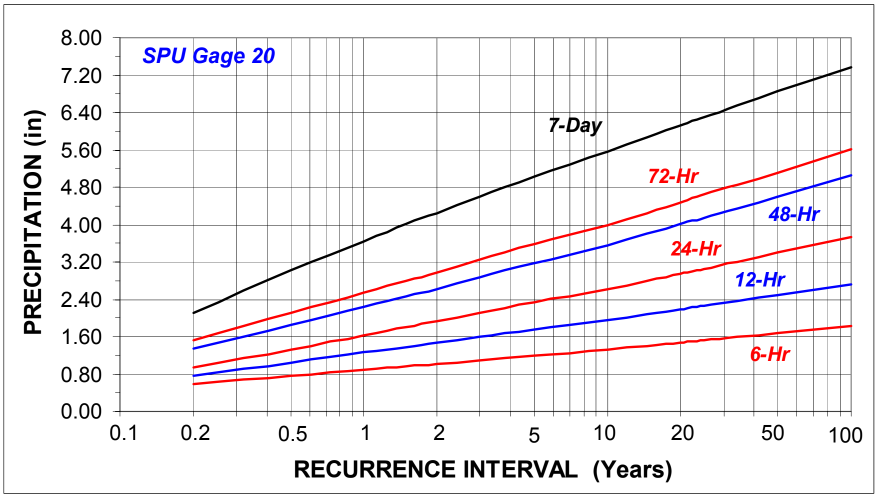
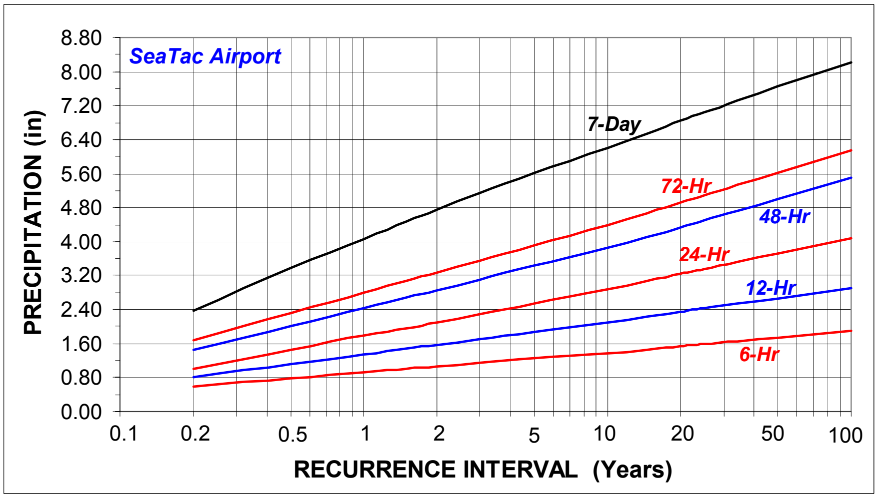


Table E-19, Figure E-19 – Precipitation-Magnitude-Frequency Estimates for SeaTac Airport

DURATION (hr)	PRECIPITATION (in)									
	RECURRENCE INTERVAL (Years)									
	0.2-YR	0.5-YR	1-YR	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
6	0.60	0.78	0.92	1.06	1.25	1.38	1.54	1.58	1.74	1.89
12	0.82	1.12	1.34	1.57	1.88	2.10	2.34	2.42	2.67	2.91
24	1.02	1.45	1.77	2.11	2.55	2.87	3.23	3.35	3.72	4.08
48	1.46	2.01	2.42	2.85	3.43	3.86	4.34	4.50	4.99	5.49
72	1.68	2.32	2.78	3.27	3.92	4.38	4.91	5.08	5.61	6.14
168	2.36	3.37	4.06	4.75	5.62	6.21	6.85	7.04	7.64	8.22



APPENDIX F

INTENSITY-DURATION-FREQUENCY VALUES FOR SEATTLE METROPOLITAN AREA

OVERVIEW

This appendix contains intensity-duration-frequency values expressed as precipitation intensity (in/hr) and depth (in) for the Seattle metropolitan area. Table F1 is a copy of Table 5 in the main report.

Table F1 – Intensity-Duration-Frequency Values for Durations from 5-Minutes through 180-Minutes for Selected Recurrence Intervals for the Seattle Metropolitan Area

DURATION (minutes)	PRECIPITATION INTENSITIES (in/hr)							
	RECURRENCE INTERVAL (Years)							
	6-Month	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
5	1.01	1.60	2.08	2.45	2.92	3.08	3.61	4.20
6	0.92	1.45	1.87	2.21	2.62	2.76	3.23	3.75
8	0.80	1.24	1.59	1.87	2.21	2.32	2.71	3.13
10	0.71	1.10	1.40	1.64	1.93	2.03	2.36	2.72
12	0.65	1.00	1.27	1.48	1.74	1.82	2.11	2.43
15	0.58	0.88	1.12	1.30	1.52	1.60	1.84	2.11
20	0.50	0.75	0.95	1.10	1.28	1.34	1.54	1.76
25	0.45	0.67	0.84	0.97	1.12	1.18	1.35	1.53
30	0.41	0.61	0.76	0.87	1.01	1.05	1.21	1.37
35	0.38	0.56	0.69	0.80	0.92	0.96	1.10	1.24
40	0.35	0.52	0.64	0.74	0.85	0.89	1.01	1.14
45	0.33	0.49	0.60	0.69	0.79	0.83	0.94	1.06
50	0.32	0.46	0.57	0.65	0.74	0.78	0.88	0.99
55	0.30	0.44	0.54	0.61	0.70	0.73	0.83	0.94
60	0.29	0.42	0.51	0.58	0.67	0.70	0.79	0.89
65	0.28	0.40	0.49	0.56	0.64	0.66	0.75	0.84
70	0.27	0.38	0.47	0.53	0.61	0.64	0.72	0.80
80	0.25	0.36	0.43	0.49	0.56	0.59	0.66	0.74
90	0.24	0.33	0.41	0.46	0.52	0.55	0.62	0.69
100	0.22	0.32	0.38	0.43	0.49	0.51	0.58	0.64
120	0.20	0.29	0.35	0.39	0.44	0.46	0.52	0.57
140	0.19	0.26	0.32	0.36	0.40	0.42	0.47	0.52
160	0.18	0.24	0.29	0.33	0.37	0.39	0.43	0.48
180	0.17	0.23	0.27	0.31	0.35	0.36	0.40	0.45

Table F2 – Intensity-Duration-Frequency Values in Inches for Durations from 5-Minutes through 180-Minutes for Selected Recurrence Intervals for the Seattle Metropolitan Area

DURATION (minutes)	PRECIPITATION DEPTH (in)							
	RECURRENCE INTERVAL (Years)							
	6-Month	2-YR	5-YR	10-YR	20-YR	25-YR	50-YR	100-YR
5	0.084	0.133	0.173	0.204	0.243	0.257	0.301	0.350
6	0.092	0.145	0.187	0.221	0.262	0.276	0.323	0.375
8	0.106	0.165	0.212	0.249	0.294	0.310	0.361	0.417
10	0.119	0.183	0.234	0.274	0.322	0.339	0.394	0.454
12	0.130	0.199	0.253	0.295	0.347	0.365	0.422	0.486
15	0.145	0.221	0.279	0.324	0.380	0.399	0.461	0.528
20	0.168	0.252	0.316	0.366	0.427	0.448	0.515	0.588
25	0.187	0.279	0.349	0.402	0.468	0.490	0.561	0.639
30	0.205	0.303	0.378	0.435	0.504	0.527	0.603	0.684
35	0.221	0.325	0.404	0.464	0.536	0.561	0.640	0.725
40	0.237	0.345	0.428	0.491	0.566	0.592	0.674	0.762
45	0.251	0.365	0.451	0.516	0.594	0.620	0.705	0.796
50	0.264	0.383	0.472	0.539	0.620	0.647	0.735	0.828
55	0.277	0.400	0.492	0.561	0.644	0.672	0.762	0.858
60	0.289	0.416	0.511	0.582	0.668	0.696	0.788	0.887
65	0.301	0.431	0.529	0.602	0.690	0.719	0.813	0.913
70	0.312	0.446	0.546	0.621	0.711	0.741	0.837	0.939
80	0.334	0.474	0.579	0.657	0.751	0.782	0.881	0.987
90	0.354	0.501	0.609	0.691	0.787	0.820	0.923	1.032
100	0.373	0.525	0.638	0.722	0.822	0.855	0.961	1.073
120	0.408	0.571	0.691	0.780	0.885	0.920	1.031	1.149
140	0.441	0.613	0.739	0.832	0.942	0.979	1.095	1.217
160	0.471	0.651	0.783	0.880	0.995	1.033	1.153	1.279
180	0.500	0.688	0.824	0.925	1.044	1.083	1.207	1.337